On the Eve of our President's Birthday : 30 June 2023

A Text Book of

Basic Electrical and Electronics Engineering

Dr. K. Saravanan
Dr. R. Sivanand
Er. A. Raja
Dr. K. Senthilkumar

Department of Electrical & Electronics Engineering

Dr. M.G.R.
EDUCATIONAL AND RESEARCH INSTITUTE
DEEMED TO BE UNIVERSITY
University with Graded Autonomy Status
(An ISO 21001 : 2018 Certified Institution)
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Chapter 1
Electric Circuits

Electrical Quantities -Ohm's Law - Kirchhoff's Laws - Series and Parallel Connection – Current Division Rule - Voltage Division Rule- Source Transformation-Y (wye) to Δ (delta) - Δ (delta) to Y (wye) - Rectangular to Polar - Polar to Rectangular

1.1 Introduction

Electric circuits are paths through which electric current flows. They are made up of different components such as wires, switches, resistors, capacitors, and batteries, that work together to control the flow of electricity. The basic concept behind an electric circuit is the flow of electrons from a power source, through the connected components, and back to the source. A complete circuit must have a closed loop for the current to flow continuously. Electric circuits can be found in many devices, including computers, household appliances, lighting systems, and electronic gadgets. Understanding how electric circuits work is essential for anyone who wants to work in electrical engineering or electronics.

1.2 Electrical Quantities

Electric Circuit: The combination of various electrical elements such as resistors, capacitors and inductors along with various energy sources such as voltage and current sources is called an electric circuit or electric network.

Charge: Charge is an electrical property of the atomic particles which matter consists. The charge of an electron is so small. Charge in motion represents current. The unit of charge is coulomb.

Current: The flow of free electrons in a metal or a conductor is called electric current. In other words, the rate of flow of charge is known as current.

$$i = \frac{dq}{dt}$$

Where, dq is the total charge transferred in coulomb. dt is the time required to transfer the charge in sec.

The unit of current is ampere. Current represented by I

Voltage: This is generally measured between two points.The voltage is defined as the ability of the charged body to do work,in moving a coulomb of charge between two points is called voltage. The unit of voltage is the volt. Voltage represented by V or v.

$$v = \frac{dw}{dq}$$

Potential Difference: The difference in the potentials of two charged bodies is called potential difference. If the potential difference is 1volt, if 1 joule of work is done in transferring 1coulomb of charge from one point to other.

EMF: The force which motivate the electron to flow in a circuit known as Electro motive force (or)EMF.

Difference between EMF and Potential Difference

Potential Difference	EMF
It causes current to flow through the circuit	It maintain the potential difference in the circuit

Electric Power: The power is defined as the rate at which work is done in an Electric circuit is called Electric power. The power is also defined as the product of voltage and current.

$$P = VI$$

$$p = \frac{dw}{dq} * \frac{dq}{dt} \quad = \frac{dw}{dt} \text{Joules / sec (or) Watt/kW/MW}$$

Electrical Energy: The total work done in an Electric Circuit is called Electrical energy (or)

Electrical energy is the product of electric power and time for which the current flow in the circuit.

$$E = p*t \qquad wh/kwh$$

Resistance: It is a property of a substance which opposes the flow of current through it. It is denoted by R and its unit is Ohm .The unit of resistance was named in honour of Georg Simon Ohm.

$$R = \rho L / A$$

Factors affecting Resistance

(i) Length – L

(ii) Area of cross section - A and

(iii) Property of the Material - ρ

1.3 Ohm's Law

Ohm's law is named for the German physicist Georg Simon Ohm, who is created with establishing the relationship between voltage and current in an ideal conductor(1827).

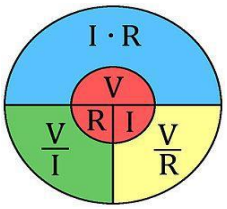
Georg Simon Ohm (1789 - 1854)

Ohm's Law states that, when the temperatures remain constant, the voltage across an ideal conductor is directly proportional to the current through it.

Mathematically, $V \propto I$ $V=IR$

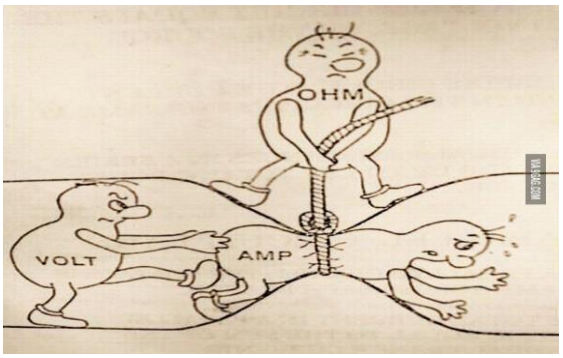
The constant of proportionality is called the "resistance", R.

Significance: Ohm's law can be expressed in three forms. It is the basic equation to solve any AC and DC circuits



Ohm's Law Physics

To understand the physics behind Ohm's law in the most simplistic manner possible, let us have a look at this picture below, and study it very closely



Limitation of Ohm's Law:

- It is not applicable to the non linear devices such as Diode,Zenerdiode,voltage regulator
- It cannot be applied to non-metallic conductor

1.4 Kirchhoff's Laws

Kirchhoff's laws,namedafter German scientist Gustav Robert Kirchhoff. Kirchhoff's laws are basic analytical tools in order to obtain the solutions of

currents and voltages for any electric circuit; whether it is supplied from a direct-current system or an alternating current system. These two laws are quite simple but extremely important.

Gustav Robert Kirchhoff
(1824-1887)

Kirchhoff's Current Law (KCL)

Statement:

The algebraic sum of currents meeting at a junction or node in an electric circuit is zero. (Or)

The sum of the currents flowing towards any junction in an electric current is equal to the sum of the currents flowing away from that junction.

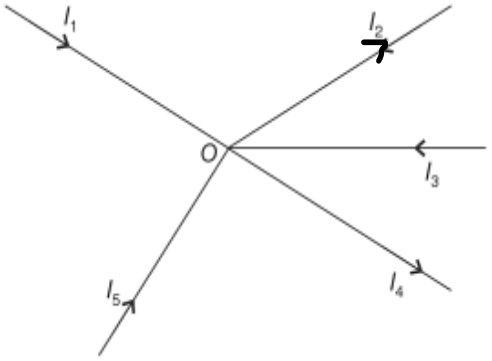
Explanation:

We have assumed that the algebraic signs of the currents entering the node are positive and therefore, that the signs of the currents leaving the node are negative. To understand the use of this law's,Consider five conductors, carrying currents, I_1,I_2,I_3,I_4 and I_5 meeting at a point O as shown in figure. If we assume the currents flowing towards the point O is taken as positive and going away as negative.

Applying Kirchhoff's law we get

$$(+I_1) + (-I_2) + (+I_3) + (-I_4) + (+I_5) = 0$$
$$I_1 - I_2 + I_3 - I_4 + I_5 = 0$$
$$I_1 + I_3 + I_5 = I_2 + I_4$$

sum of incoming currents = sum of outgoing currents.



The law is very helpful in Network Simplifications.

Kirchhoff's Voltage Law (KVL)

Statement:

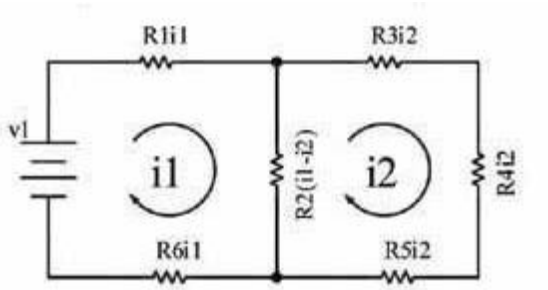
In any closed-loop network, the total voltage around the loop is equal to the sum of all the voltage drops within the same loop, which is also equal to zero. In other words, the algebraic sum of all voltages within the loop must be equal to zero.

$$\sum_{i=1}^{n} I_i R_i + E_i = 0$$

Explanation:

Kirchhoff's voltage law can be stated in words as the sum of all voltage drops and rises in a closed loop equals zero. As the image below demonstrates, loop 1 and loop 2 are both closed loops within the circuit. The sum of all voltage drops and rises around loop 1 equals zero, and the sum of all voltage drops and rises in loop 2 must also equal zero. A closed loop can be defined as any path in which the originating point in the loop is also the ending point for the loop. No matter how the loop is defined or drawn, the sum of the voltages in the loop must be

zero.



$$-v1 + R1\,i1 + R2(i1-i2) + R6i2 = 0$$

$$R2(i2-i1) + R3\,i2 + R4i2 + R5i2 = 0$$

The law is very useful in the loop analysis of the network.

Voltage Drop: When current flows through an element, the voltage produced across that element is known as voltage drop

The terms Node, Loop and Branch

A **Node** is a junction where two or more circuit elements are connected together

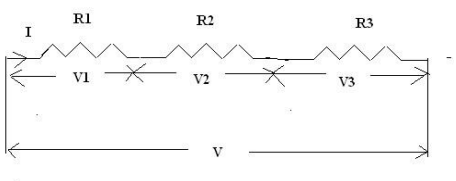
A **Branch** in an electrical circuit is that part of a circuit which lies between two junction points.

A **Loop** is any closed path of a circuit through which the electric current passes.

A **Mesh** is the most elementary form of a loop and cannot be further divided into other loops. But a loop cannot be called as mesh.

1.5Series and Parallel Connection

1.5.1 Series connection:



The resistors R1, R2, R3 are connected in series across the supply voltage V. The total current flowing through the circuit is denoted as I. The voltage across the resistor R1, R2 and R3 is V1, V2, and V3 respectively.

$V_1 = I*R_1$ (as per ohms law)

$V_2 = I*R_2$

$V_3 = I*R_3$

$V = V_1+V_2+V_3$

$= I * R_1+I * R_2+I * R_3$

$= (R_1+R_2+R_3) * I$

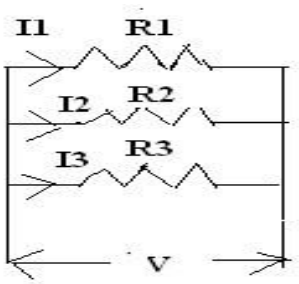
$I * R = (R_1+R_2+R_3) * I$

$$\mathbf{R = R_1+R_2+R_3}$$

Characteristics of Series Circuit:

1. The same current flows through each resistance.
2. The supply voltage is the sum of the individual voltage drops across the Resistance i.e. V= $V_1 + V_2 + V_3 + \ldots\ldots + V_n$
3. The equivalent resistance is equal to the sum of the individual resistances.
4. The equivalent resistance is the largest of all the individual resistances.

1.5.2 Parallel Connection:



The resistors R_1, R_2, R_3 are connected in parallel across the supply voltage V. The total current flowing through the circuit is denoted as I. The current flowing through the resistor R1, R2 and R3 is I1, I2, and I3

respectively.

$$I = V / R \text{ (as per ohms law)}$$

$$I_1 = V_1 / R_1$$

$$I_2 = V_2 / R_2$$

$I_3 = V_3 / R_3$

$V_1 = V_2 = V_3 = V$

From the above diagram

$I = I_1 + I_2 + I_3$

$= V_1 / R_1 + V_2 / R_2 + V_3 / R_3$

$= V / R_1 + V/R_2 + V/R_3$

$I = V (1/R_1 + 1/R_2 + 1/R_3)$

$V / R = V (1/R_1 + 1/R_2 + 1/R_3)$

$1/R = 1/R_1 + 1/R_2 + 1/R_3$

Characteristics of Parallel Circuit:

1. The total current gets divided into the number of paths equal to the number of resistances in parallel. The total current is always sum of all the individual currents i.e. $I = I_1 + I_2 + I_3 + \ldots + I_n$
2. The same potential difference gets across the resistance in parallel.
3. The reciprocal of the equivalent resistance of a parallel circuit is equal to the sum of the reciprocal of the individual resistances.
4. The equivalent resistance is the smallest of all the individual resistances.

Reason for Domestic Appliances are Connected in Parallel:

The electrical appliances are rated for same voltages but different power hence can be connected in parallel without affecting their individual performance. If a break occurs in any one branch of the circuit, it will have no effect on the other.

Comparison of Series and Parallel Circuits:

S.No	Series circuit	Parallel circuit
1	The same current flows through each resistance	The same voltage exist across all the resistances in parallel
2	The voltage across each resistance is different	The current through each resistance is different
3	The sum of the voltages across all the resistances is the supply voltage V= $\boldsymbol{V_1 + V_2 + V_3 + \ldots + V_n}$	The sum of the currents through all the resistances is the supply current I = $\boldsymbol{I_1 + I + I_3 + \ldots . + I_n}$

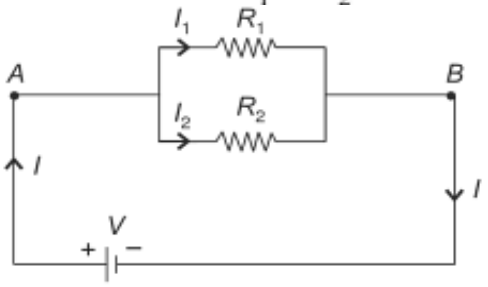
1.6 Current Division Rule

Two resistances R_1 and R_2 are connected in parallel across a battery of V volts. Current through R_1 is I_1 and through R_2 is I_2. The total resistance R_T is

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$= \frac{R_2 + R_1}{R_1 R_2}$$

$$R_T = \frac{R_1 R_2}{R_1 + R_2}$$



Hence the total value of two resistances connected in parallel is equal to their product divided by their sum. The branch currents I_1 and I_2 can be deduced as

$$V = IR_T = I\frac{R_1R_2}{R_1 + R_2}$$

By applying ohm's law the current through the resistance R_1

$$I_1 = \frac{V}{R_1} = I\frac{R_2}{R_1+R_2}$$

And current through the resistance R_2

$$I_2 = \frac{V}{R_2} = I\frac{R_1}{R_1+R_2}$$

The general expression using current division rule,

I in any branch = Total current*Front Resistance/ Branch Resistance+Front Resistance

1.7 Voltage Division Rule

Consider the resistances R_1,R_2, R_3,……..R_n be connected in series across a battery of V volts. The current flowing through all the resistances is same as shown in figure.

For n resistances in series the equivalent resistance is

$R_T = R_s = R_1 + R_2 + R_3 + \ldots\ldots + R_n$

By Ohm's law the current through the series circuit

$$I = \frac{V}{R_T}$$

Voltage across each resistance is

$$V_1 = IR_1,\ V_2 = IR_2 \ldots\ V_x = IR_x \ldots.;\ V_n = IR_n$$

i.e. $$V_1 = \frac{V}{R_T}R_1;\ V_2 = \frac{V}{R_T}R_2;\ \ldots\ V_x = \frac{V}{R}R_x$$

∴ Voltage across any resistance in the series circuit

$$= V_x\frac{R_x}{R_T}V$$

Problem 1.1 Three resistances of values 2Ω, 3Ω and 5Ω are connected in series across 20 V, D.C supply Calculate (a) equivalent resistance of the circuit (b) the total current of the circuit (c) the voltage drop across each resistor and (d) the power dissipated in each resistor.

Given data:

$R_1 = 2\Omega$

$R_2 = 3\Omega$

$R_3 = 5\Omega$

$V = 20V$

To find:

$R_T = ?$

$I_T = ?$

$V_1, V_2, V_3 = ?$

$P_1, P_2, P_3 = ?$

Formula used:

$R_T = R_1+R_2+R_3$ (series connection)

$I_T = V_T / R_T$

$V_1 = R_1*I_1, V_2 = R_2*I_2, V3 = R_3*I_3$

$P_1=V_1*I_1, P_2=V_2*I_2, P_3=V_3*I_3$

Solution:

$R_T = R_1+R_2+R_3 = +3+5$ **$R_T = 10\Omega$**

$I_T = V_T / R_T = 20 / 10$ **$I_T = 2$ A**

In Series Connection $I_1 = I_2 = I_3 = I_T = 2A$

$V_1 = I_1*R_1 = 2*2$ **$V_1 = 4$ V**

$V_2 = I_2*R_2 = 2*3$ **$V_2 = 6$ V**

$V_3 = I_3*R_3 = 5*2$ **$V_3 = 10V$**

$P_1 = V_1*I_1 = 4*2$ **$P_1 = 8W$**

$P_2 = V_2*I_2 = 6*2$ **$P_2 = 12W$**

$P_3 = V_3*I_3 = 10*2$ **$P_3 = 20W$ Result:**

Answer:

(a) Equivalent resistance of the circuit $R_T = 10\Omega$

(b) The total current of the circuit $I_T = 2A$

(c) Voltage drop across each resistor $V_1 = 4$ V, $V_2 = 6$ V, $V_3 = 10$V

(d) The power dissipated in each resistor $P_1 = 8$W, $P_2 = 12$W, $P_3 = 20$W

1.8 Delta to Star Transformation

Equations for Delta to Star Transformation

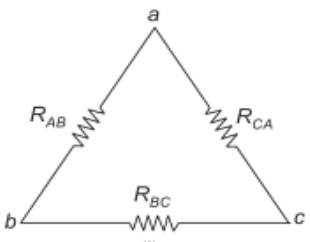
Circuit configuration is often encountered in which the resistors do not appear to be in series or parallel. Under these conditions, it may be necessary to convert the circuit from one form to another in order to solve for unknown quantities.

Standard 3-phase circuits or networks take on two major forms with names that represent the way in which the resistances are connected, a **Star** connected network which has the symbol of the letter, Y (wye) and a **Delta** connected network which has the symbol of a triangle, Δ (delta).

This process allows us to produce a mathematical relationship between the various resistors giving us a **Star -Delta Transformation** as well as a **Delta-Star Transformation**.

To convert a delta network to an equivalent star network we need to derive a transformation formula for equating the various resistors to each other between the various terminals. Consider the circuit below.

In Delta network, the 3 resistors are connected one and other forming a loop,



The Equivalent Resistance between the terminals a and b in delta form is

R_{AB} Parallel with $(R_{BC} + R_{CA})$

$$\frac{1}{R_{ab}} = \frac{1}{R_{AB}} + \frac{1}{R_{BC} + R_{CA}}$$

$$\frac{1}{R_{ab}} = \frac{R_{AB} + R_{BC} + R_{CA}}{R_{AB}(R_{BC} + R_{CA})}$$

$$R_{ab} = \frac{R_{AB}(R_{BC}+R_{CA})}{R_{AB}+R_{BC}+R_{CA}} \quad \text{--------- (1)}$$

Similarly, Equivalent Resistance between the terminals b and c in delta form is

R_{CB} Parallel with $(R_{CA} + R_{AB})$

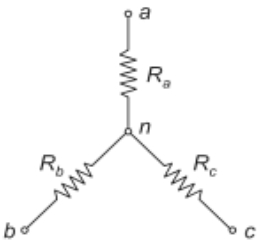
$$R_{bc} = \frac{R_{BC}(R_{CA}+R_{AB})}{R_{AB}+R_{BC}+R_{CA}} \quad \text{--------- (2)}$$

Finally, Equivalent Resistance between the terminals c and a in delta form is

R_{CA} Parallel with $(R_{AB} + R_{BC})$

$$R_{ca} = \frac{R_{CA}(R_{AB}+R_{BC})}{R_{AB}+R_{BC}+R_{CA}} \text{--------(3)}$$

In Star Network, one end of each resistors are connected together



Equivalent Resistance between the terminals a and b is $R_{ab} = R_a + R_b$- --- (4)

Equivalent Resistance between the terminals b and c is$R_{bc} = R_b + R_c$--------- (5)

Equivalent Resistance between the terminals c and a is $R_{ca} = R_c + R_a$ -……(6)

Using this 6 equations

Equating equation (1) and (4), we get

$$R_a + R_b = \frac{R_{AB}(R_{BC}+R_{CA})}{R_{AB}+R_{BC}+R_{CA}} \quad \text{---------(7)}$$

In a similar manner, equating equation (2) and (5), we get

$$R_b + R_c = \frac{R_{BC}(R_{AB}+R_{CA})}{R_{AB}+R_{BC}+R_{CA}} \quad \text{------} \quad (8)$$

Finally, equating equation (3) and (6) , we get

$$R_c + R_a = \frac{R_{CA}(R_{AB}+R_{BC})}{R_{AB}+R_{BC}+R_{CA}} \quad \text{------} \quad (9)$$

Subtracting (7) from (8) we get

$$(R_a + R_b) - (R_b + R_c) = \frac{R_{AB}(R_{BC}+R_{CA})}{R_{AB}+R_{BC}+R_{CA}} - \frac{R_{BC}(R_{AB}+R_{CA})}{R_{AB}+R_{BC}+R_{CA}}$$

Taking LCM and simplifying we get

$$R_a - R_c = \frac{R_{AB}R_{CA}-R_{BC}R_{CA}}{R_{AB}+R_{BC}+R_{CA}} \quad \text{------- (10)}$$

Adding equation (9) and (10) we get

$$R_c + R_a + R_a - R_c = \frac{R_{CA}(R_{AB}+R_{BC})}{R_{AB}+R_{BC}+R_{CA}} + \frac{R_{AB}R_{CA}-R_{BC}R_{CA}}{R_{AB}+R_{BC}+R_{CA}}$$

Simplifying we get $2R_a = \frac{2R_{CA}R_{AB}}{R_{AB}+R_{BC}+R_{CA}}$ ------- (11)

$$R_a = \frac{R_{CA}R_{AB}}{R_{AB}+R_{BC}+R_{CA}} \quad \text{------ (12)}$$

Similarly we get for other resistances as

$$R_b = \frac{R_{BC}R_{AB}}{R_{AB}+R_{BC}+R_{CA}} \quad \text{-------- (13)}$$

$$R_c = \frac{R_{CA}R_{BC}}{R_{AB}+R_{BC}+R_{CA}} \text{--------- (14)}$$

This will be the equivalent resistance of Star.

1.9 Star to Delta Transformation

Equations for Star to Delta Transformation:

To convert a star network to an equivalent delta network, we need to use the transformation formula of delta to star.

$$R_a = \frac{R_{CA}R_{AB}}{R_{AB}+R_{BC}+R_{CA}} \text{---- (12)}$$

$$R_b = \frac{R_{BC}R_{AB}}{R_{AB}+R_{BC}+R_{CA}} \text{----- (13)}$$

$$R_c = \frac{R_{CA}R_{BC}}{R_{AB}+R_{BC}+R_{CA}} \text{ ------ (14)}$$

Dividing equation (12) by (13) ,we get

$$\frac{R_a}{R_b} = \frac{\frac{R_{AB}R_{AC}}{R_{AB}+R_{BC}+R_{AC}}}{\frac{R_{AB}R_{BC}}{R_{AB}+R_{BC}+R_{AC}}} = \frac{R_{AC}}{R_{BC}}$$

$$R_{AC} = R_{BC}\frac{R_a}{R_b} \quad \text{-----} \quad (15)$$

Dividing equation (12) by (14), we get

$$\frac{R_a}{R_c} = \frac{\frac{R_{AB}R_{CA}}{R_{AB}+R_{BC}+R_{AC}}}{\frac{R_{CA}R_{BC}}{R_{AB}+R_{BC}+R_{AC}}} = \frac{R_{AB}}{R_{BC}}$$

$$R_{AB} = R_{BC}\frac{R_a}{R_c} \text{ -------- (16)}$$

Substituting equation (15) and (16) in (12), we get

$$R_a = \frac{R_{BC}\frac{R_a}{R_b}R_{BC}\frac{R_a}{R_c}}{R_{BC}\frac{R_a}{R_c}+R_{BC}+R_{BC}\frac{R_a}{R_b}}$$

$$R_a = \frac{{R_{BC}}^2\frac{{R_a}^2}{R_cR_b}}{R_{BC}\left[\frac{R_a}{R_c}+1+\frac{R_a}{R_b}\right]}$$

$$R_a = \frac{\frac{{R_a}^2}{R_cR_b}R_{BC}}{\left[\frac{R_aR_b+R_cR_b+R_cR_a}{R_cR_b}\right]}$$

$$R_{BC} = \left[\frac{R_aR_b+R_cR_b+R_cR_a}{R_a}\right] \text{ -------- (17)}$$

Similarly we can derive for R_{AB}&R_{CA}

$$R_{AB} = \left[\frac{R_aR_b+R_cR_b+R_cR_a}{R_c}\right] \text{ -------- (18)}$$

$$R_{CA} = \left[\frac{R_aR_b+R_cR_b+R_cR_a}{R_b}\right] \text{ -------- (19)}$$

This will be the equivalent resistance of Delta.

The equivalent resistance between the terminals a, b and c is R_{AB}, R_{BC} and R_{CA} . When the two networks are electrically equivalent, the resistances between the terminals as measured in star and delta must be same.

1.10 Rectangular to Polar and Polar to Rectangular Conversion

Complex Algebra:

We know that the scalar quantity has only magnitude where as a vector quantity has both magnitude and direction. The various forms of representing a vector quantity are

- Rectangular form
- Polar form
- Trignometrical form
- Exponential form

In this chapter the first and second forms of vector representation are importance to us.

Rectangular form

A vector can be expressed in terms of its rectangular (horizontal and vertical) components. For example, in the following figure, OP (representing the vector A) is specified in terms of its horizontal component 'a' and vertical component 'b'.

Thus $A=a+jb$ …… (i)

Where j is an operator indicating that b is perpendicular to a.

The vector form expressed in eqn(i) is also called complex form, where a is the in-phase or active component and b is the qudrature or reactive component.

Polar form

The magnitude of vector A is given by

$$|A| = \sqrt{a^2+b^2} \quad \text{…… (ii)}$$

And its angle with X-axis is given by

$$\Phi = \tan^{-1}\left(\frac{b}{a}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(iii)}$$

from equation (ii) and (iii) we can represent the vector A as

$$\text{vector A} = |A| L\Phi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(iv)}$$

Where $|A|$ and Φ are given by equation (ii) and (iii). Equation (iv)gives the polar form representation of the vector A.

j operator

j means anti clockwise rotation of the vector through 90^0, also $j = \sqrt{-1}$

j^2 means anti clockwise rotation of the vector through 180^0, also $j^2 = -1$

j^3 means anti clockwise rotation of the vector through 270^0, also $j^3 = -j$

j^4 means anti clockwise rotation of the vector through 270^0, also $j^4 = +1$

$$1/j = j/j\,j = j/-1 = -j$$

Note: Addition and subtraction can be easily done in rectangular form. Multiplication and division easily done in polar form.

Addition subtraction of complex quantities:

Let us consider two vector quantities

$\overline{P_1} = a_1 + jb_1$ and $\overline{P_2} = a_2 + jb_2$

1) Addition

$$\overline{P} = \overline{P_1} + \overline{P_2}$$

$$= a_1 + jb_1 + a_2 + jb_2$$

$$= (a_1 + a_2) + j(b_1 + b_2)$$

The magnitude of vector, $P = \sqrt{(a_1 + a_2)^2 + (b_1 + b_2)^2}$

Angle of vector P with X-axis

$\theta = \tan^{-1}\left(\frac{b_1+b_2}{a_1+a_2}\right)$

2) Subtraction

$$Q = \overline{P_1} - \overline{P_2}$$

$$= (a_1 + jb_1) - (a_2 + jb_2)$$

$= a_1 + jb_1 - a_2 - jb_2$

$=(a_1 - a_2) + j(b_1 - b_2)$

Magnitude of vector Q = $\sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2}$

Angle of vector Q with X-axis

$$Q= \tan^{-1}\left(\frac{b_1-b_2}{a_1-a_2}\right)$$

3) Multiplication

$\overline{R} = \overline{P_1} \times \overline{P_2}$

$= (a_1 + jb_1) \times (a_2 + jb_2)$ $[j^2= -1]$

$= a_1a_2 + jb_1a_2 + jb_2 a_1 + j^2b_1b_2$

$= (a_1a_2 - b_1b_2)+ (a_1b_2+ b_1a_2)$

Magnitude of $\overline{R}$ $=\sqrt{(a_1a_2 - b_1b_2)^2 + (a_1b_2 + b_1a_2)^2}$

If angle with respect to X-axis

$$=\tan^{-1}\left(\frac{a_1b_2+b_1a_2}{a_1a_2-b_1b_2}\right)$$

4) Division

$$\overline{S} = \frac{\overline{P_1}}{\overline{P_2}} = \frac{a_1+ jb_1}{a_2+ jb_2}$$

$$= \frac{a_1+ jb_1}{a_2+ jb_2} \times \frac{(a_2- jb_2)}{(a_1- jb_1)} \quad [j^2= -1]$$

$$= \frac{a_1a_2+jb_1a_2- ja_1b_2 -j^2b_1b_2}{a_2^2+ b_2^2}$$

$$= \frac{a_1a_2+b_1b_2+ jb_1 a_2-ja_1b_2}{a_2^2+ b_2^2}$$

$$\overline{S}= \frac{a_1a_2+b_1b_2}{a_2^2+ b_2^2} + j\frac{(b_1a_2-a_1b_2)}{a_2^2+ b_2^2}$$

Problem 1.2 Find the value of the following:-

1) Z_1+Z_2

2) Z_1Z_2

3) $(Z_1Z_2)/(Z_1+Z_2)$

4) $Z_3+\frac{Z1Z2}{Z1+Z2}$

Given,

Rectangular form

$Z_1 = 5+ j94.25$

$Z_2 = 10+ j212.2$

$Z_3=15+ j80$

Solution 1:

Polar form of Z_1

$|Z_1| = \sqrt{a^2 + b^2}$

$= \sqrt{5^2 + (94.25)^2}$

$= \sqrt{25 + 888.625}$

$= \sqrt{8408.0625}$

$|Z_1| = 94.38$

Angle $\Phi = \tan^{-1}\frac{b}{a}$

$= \tan^{-1}\frac{94.25}{5}$

$= \tan^{-1} 18.85$

$\Phi = 86.96$

Polar form of Z_1 is $94.38 \angle 86.96$

Solution 2:

Polar form of Z_2

$|Z_2| = \sqrt{10^2 + (212.2)^2}$

$= \sqrt{100 + 45028.814}$

$= \sqrt{45128.84}$

$|Z_2| = 212.44$

Angle $\theta = \tan^{-1}(\frac{-212.2}{10})$

$= \tan^{-1}(-21.22)$

$\theta = -87.29$

Polar form of Z_2 is $212.44 \angle -87.29$

1) $Z_1+Z_2=5+ j94.25 + 10 – j212$

$= 15–j117.96$

2)$Z_1Z_2= (94.38 \angle 86.96)\times(212.44 \angle -87.29)\times(-87.29+86.96)$

$= 20050.68 \angle -0.34$

3) Z_1Z_2 /Z_1+Z_2=Polar form ofZ_1Z_2

$|Z_1+Z_2| = \sqrt{15^2 + (117.96)^2}$

$= \sqrt{225 + 13914.56}$

$= \sqrt{14139.56}$

$|Z_1+Z_2| = 118.9$

Polar form of $Z_1+Z_2=118.9 \angle -82.75$

Angle $\theta = \tan^{-1}(\frac{-117.96}{15})$

$= \tan^{-1}(-7.864)$

$\theta = -82.75$

$Z_1Z_2/Z_1+Z_2= \frac{20050.08 \ L-0.34}{118.9 \ L-82.75}$

$Z_1Z_2/Z_1+Z_2=168.6 \angle 82.41$

$|Z| = \sqrt{168.6}$

$= \sqrt{a^2 + b^2}$

$=168.6$

$\sqrt{a^2 + b^2}$ = 168.6

$a^2 + b^2$ = 248425.96

$a^2 + 56.3a^2$=28425.96

$57.31a^2$=28425.96

$a^2 = \frac{28425.96}{57.31}$ = 496

a =22.27

And

Angle Φ =82.41

$\tan^{-1}\frac{b}{a}$ =82.41

$\frac{b}{a}$ =tan 82.41

b=7.504 (a)

= 7.504×2271

So, b=16711

4) $Z_3 + \frac{Z1Z2}{Z1+Z2}$ = (15 + j80) + (22.27 + j167.11)

=37 + j247.11

Chapter 2
Electron Devices

Passive Circuit Components – Classification of Semiconductor – PN Junction Diode – Zener Diode – Operating Principle – BJT – JFET – SCR – MOSFET – IGBT - Characteristics and Applications

2.1 Introduction

Electron devices refer to electronic components that utilize the flow of electrons for their functioning. These devices include vacuum tubes, transistors, diodes and integrated circuits. Electron devices have revolutionized the field of electronics and have helped in its growth over time. They are used in a wide range of applications such as communication systems, digital circuits, power electronics, and many more.

Vacuum tubes were the first electron devices that were developed in the early 20th century. They were used in radios, televisions, and early computers until the development of the transistor in the late 1940s. Transistors replaced vacuum tubes and were much smaller, cheaper, and more reliable. They became the mainstay of electronic devices.

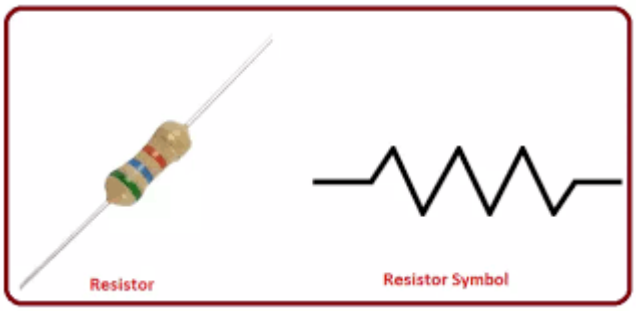
Diodes are devices that allow current to flow in only one direction. They are used in rectifiers, which convert AC to DC, and in signal processing circuits. Integrated circuits (ICs) are multiple electronic components integrated into a single chip. They have revolutionized the electronics industry by allowing for miniaturization and increased functionality of electronic devices.

Overall, electron devices have played a critical role in the development of modern technology, and continue to drive innovation and advancement today.

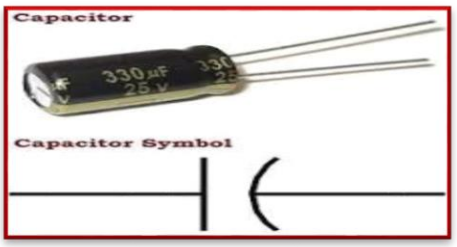
2.2 Passive Circuit Components

Passive circuit components are electronic components that do not require an external power source to function. They are used in electronic circuits to modify and control the flow of electric current. The three main types of passive circuit components are resistors, capacitors, and inductors.

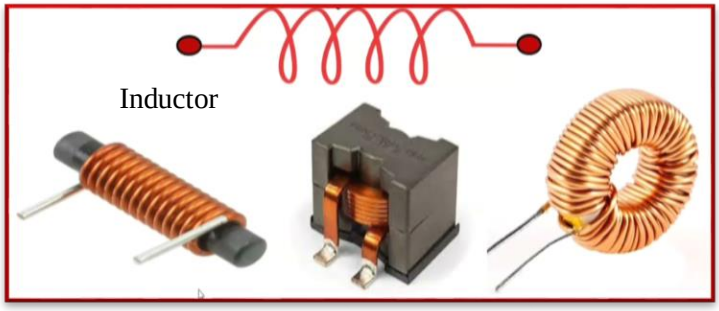
1. **Resistors:** A resistor is an electrical component that resists the flow of electric current. It is used to limit the amount of current that flows through a circuit and to reduce the voltage level. Resistors are commonly used in voltage dividers, current limiters, and signal conditioning circuits.



2. **Capacitors:** A capacitor is an electrical component that stores electric charge. It consists of two conducting plates separated by an insulating material called a dielectric. Capacitors are used to filter out noise in electronic circuits, to store electrical energy, and to create timing circuits.



3. **Inductors:** An inductor is an electrical component that stores energy in a magnetic field when electric current flows through it. It consists of a coil of wire that generates a magnetic field when a current flows through it. Inductors are used in circuits that require a specific level of inductance, such as in power supplies, filters, and oscillators.



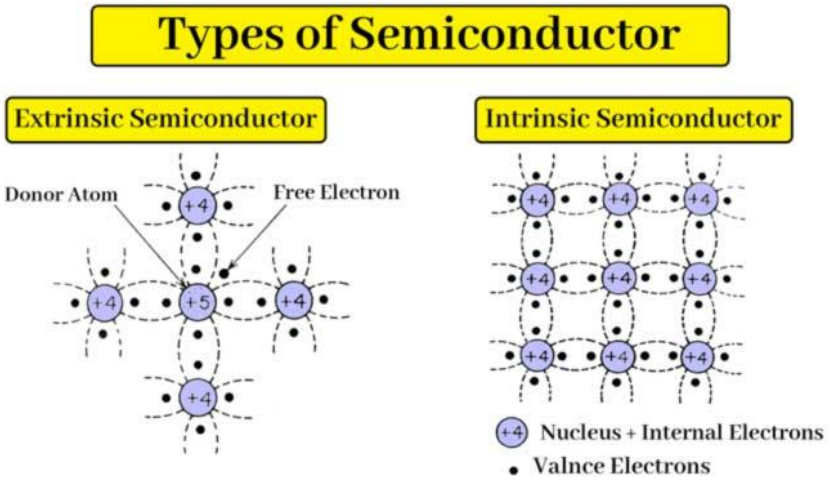
Other examples of passive circuit components include diodes, transformers, and resistive loads. These components play a crucial role in electronic circuit design and are essential for building electronic devices.

2.3 Classification of Semiconductors

Semiconductors are materials that have electrical conductivity between that of a conductor and an insulator. They are used in electronic devices such as transistors, diodes, and integrated circuits. Semiconductors can be classified into two main categories: intrinsic semiconductors and extrinsic (doped) semiconductors.

1. **Intrinsic Semiconductors:** Intrinsic semiconductors are pure semiconducting materials that have no intentional impurities added to them. They have a specific number of electrons in their valence band and a specific number of holes in their conduction band. Intrinsic semiconductors are typically made of materials such as silicon, germanium, and diamond.
2. **Extrinsic (Doped) Semiconductors:** Extrinsic semiconductors are semiconducting materials that have intentional impurities added to them. This process is called doping, and it is done by introducing small

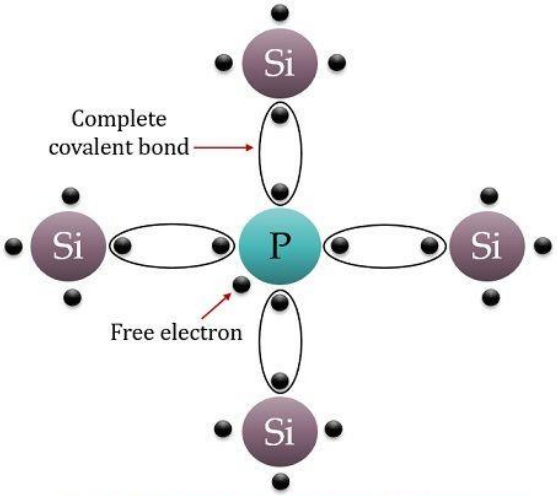
amounts of other elements into the crystal lattice structure of the semiconductor. Doping can either increase or decrease the number of free electrons or holes in the semiconductor material, thereby changing its electrical properties.



There are two main types of doped semiconductors:

- **N-type Semiconductors:** An N-type semiconductor is a type of extrinsic semiconductor material that has been doped with impurities that provide excess free electrons. The term "N" stands for "negative" because the excess electrons in the material give it a net negative charge.

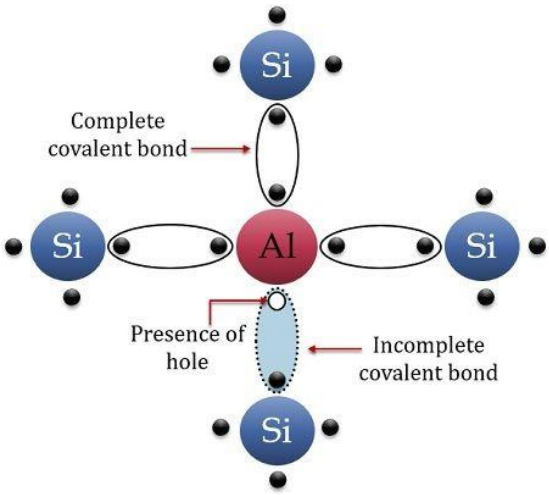
The doping process involves adding impurities such as phosphorus, arsenic, or antimony to the crystal structure of the semiconductor material, such as silicon or germanium. These impurities are called donor impurities because they donate an extra electron to the crystal lattice structure of the semiconductor material.



- Si = Intrinsic semiconductor atom
- P = Pentavalent impurity atom

Formation of N type extrinsic semiconductor

- **P-type Semiconductors:** A P-type semiconductor is a type of extrinsic semiconductor material that has been doped with impurities that provide excess holes or positive charge carriers. The term "P" stands for "positive" because the excess holes in the material give it a net positive charge.



- Si = Intrinsic semiconductor atom
- Al = Trivalent impurity atom

Formation of P type extrinsic semiconductor

The doping process involves adding impurities such as boron, aluminum, or gallium to the crystal structure of the semiconductor material, such as silicon or germanium. These impurities are called acceptor impurities because they accept an electron from the crystal lattice structure of the semiconductor material, leaving behind a hole.

The combination of N-type and P-type semiconductors creates a p-n junction, which is the basic building block of most semiconductor devices.

Silicon and Germanium

Silicon and germanium are two of the most commonly used semiconducting materials in electronic devices.

Silicon (Si) is the most widely used semiconductor material in the electronics industry due to its abundance, low cost, and excellent electrical properties. It has a bandgap energy of 1.1 eV, which means that it requires a relatively small amount of energy to move an electron from the valence band to the conduction band. Silicon is typically used to make transistors, diodes, and integrated circuits.

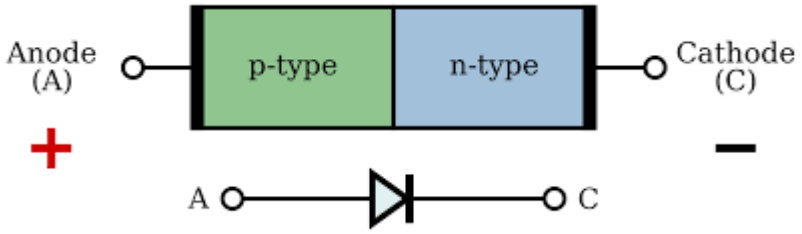
Germanium (Ge) was widely used as a semiconductor material in the early days of the electronics industry but has been largely replaced by silicon due to its high cost and limited availability. Germanium has a bandgap energy of 0.7 eV, which is lower than that of silicon, meaning it requires less energy to excite electrons to the conduction band. Germanium is still used in some niche applications, such as infrared detectors and high-speed amplifiers.

Both silicon and germanium have similar crystal structures, consisting of a diamond-like lattice structure. They both have four valence electrons, making them tetravalent, which means they can form covalent bonds with other atoms

to create a stable crystal structure. When doped with impurities, they can become either N-type or P-type semiconductors and are essential for the manufacture of many electronic devices.

2.4 PN Junction Diode

A PN junction diode is a type of semiconductor device that is formed by joining together a P-type semiconductor and an N-type semiconductor. When the P-type and N-type semiconductors are joined together, a PN junction is formed at the interface between them.

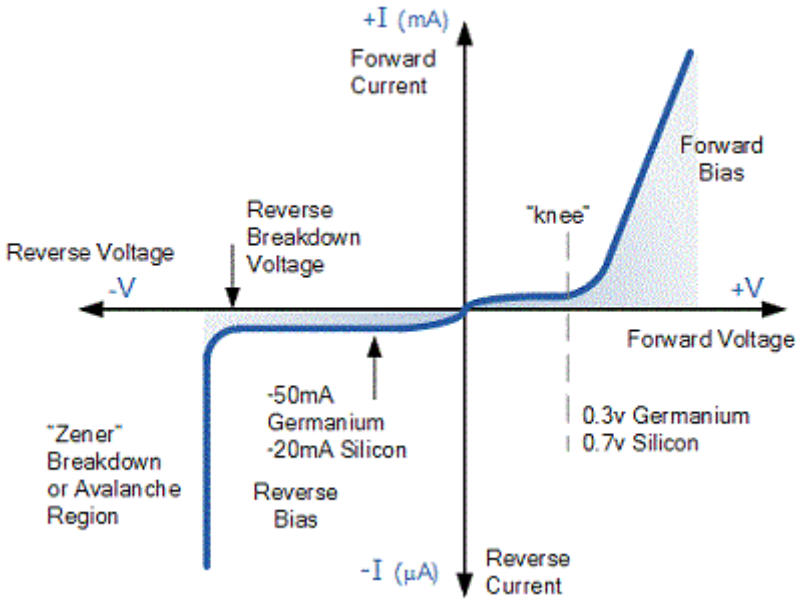


The PN junction diode works by allowing current to flow in one direction while blocking it in the opposite direction. When a voltage is applied to the diode in the forward bias direction (positive voltage applied to the P-type region and negative voltage applied to the N-type region), the excess electrons in the N-type region move towards the P-type region and combine with the holes in that region, creating a depletion region at the junction.

The depletion region acts as a barrier to further current flow in the forward bias direction, but if the voltage applied is high enough, the barrier can be overcome, and current will flow through the diode. This is known as the forward current or forward bias current.

In the reverse bias direction (negative voltage applied to the P-type region and positive voltage applied to the N-type region), the excess electrons in the P-type region move towards the N-type region, and the holes in that region move towards the P-type region. This increases the width of the depletion region,

making it even more difficult for current to flow through the diode. This is known as the reverse current or reverse bias current.



PN junction diodes have several important characteristics that make them useful in a variety of electronic applications:

1. **Forward bias current:** When a voltage is applied to the PN junction diode in the forward bias direction, the diode allows current to flow easily. This makes PN junction diodes useful as rectifiers, which convert AC voltage to DC voltage.

2. **Reverse bias voltage:** When a voltage is applied to the PN junction diode in the reverse bias direction, the diode blocks current flow. This makes PN junction diodes useful in voltage regulators, which maintain a constant voltage output.

3. **Low voltage drop:** PN junction diodes have a very low voltage drop in the forward bias direction, which means they can be used to regulate voltage without wasting much power.

4. **Fast switching speed:** PN junction diodes can switch on and off very quickly, which makes them useful in digital circuits.

Some common applications of PN junction diodes include:

1. **Rectification:** PN junction diodes are commonly used in rectifier circuits to convert AC voltage to DC voltage.
2. **Voltage regulation:** PN junction diodes are used in voltage regulator circuits to maintain a constant output voltage.
3. **Signal detection:** PN junction diodes can be used to detect and demodulate radio signals.
4. **Protection:** PN junction diodes can be used to protect electronic circuits from voltage spikes and transients.
5. **Lighting:** PN junction diodes are used in light-emitting diodes (LEDs) to produce light.

2.5 Zener Diode

A Zener diode is a special type of device designed to operate in the zener breakdown region. Zener diodes acts like normal p-n junction diodes under forward biased condition. When forward biased voltage is applied to the zener diode it allows large amount of electric current and blocks only a small amount of electric current.

Zener diode is heavily doped than the normal p-n junction diode. Hence, it has very thin depletion region. Therefore, zener diodes allow more electric current than the normal p-n junction diodes.

Zener diode allows electric current in forward direction like a normal diode but also allows electric current in the reverse direction if the applied reverse voltage

is greater than the zener voltage. Zener diode is always connected in reverse direction because it is specifically designed to work in reverse direction.

Zener diode definition

A zener diode is a p-n junction semiconductor device designed to operate in the reverse breakdown region. The breakdown voltage of a zener diode is carefully set by controlling the doping level during manufacture.

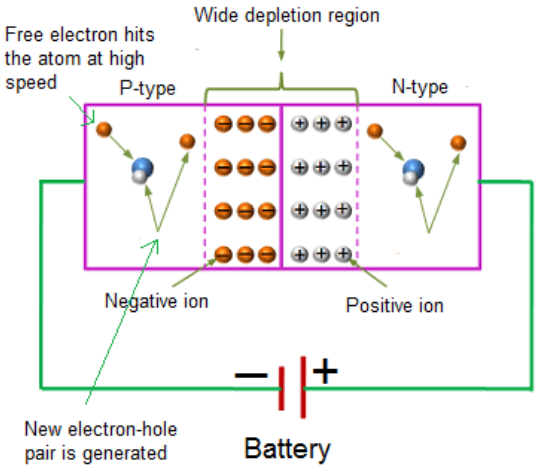
The name zener diode was named after the American physicist Clarance Melvin Zener who discovered the zener effect. Zener diodes are the basic building blocks of electronic circuits. They are widely used in all kinds of electronic equipments. Zener diodes are mainly used to protect electronic circuits from over voltage.

Breakdown in zener diode

There are two types of reverse breakdown regions in a zener diode: avalanche breakdown and zener breakdown.

Avalanche breakdown

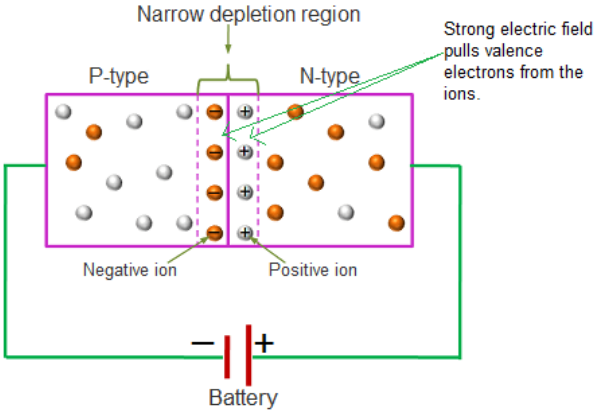
The avalanche breakdown occurs in both normal diodes and zener diodes at high reverse voltage. When high reverse voltage is applied to the p-n junction diode, the free electrons (minority carriers) gains large amount of energy and accelerated to greater velocities.



The free electrons moving at high speed will collides with the atoms and knock off more electrons. These electrons are again accelerated and collide with other atoms. Because of this continuous collision with the atoms, a large number of free electrons are generated. As a result, electric current in the diode increases rapidly. This sudden increase in electric current may permanently destroys the normal diode. However, avalanche diodes may not be destroyed because they are carefully designed to operate in avalanche breakdown region. Avalanche breakdown occurs in zener diodes with zener voltage (V_z) greater than 6V.

Zener breakdown

The zener breakdown occurs in heavily doped p-n junction diodes because of their narrow depletion region. When reverse biased voltage applied to the diode is increased, the narrow depletion region generates strong electric field.

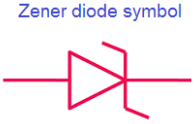


When reverse biased voltage applied to the diode reaches close to zener voltage, the electric field in the depletion region is strong enough to pull electrons from their valence band. The valence electrons which gains sufficient energy from the strong electric field of depletion region will breaks bonding with the parent atom. The valance electrons which break bonding with parent atom will become free electrons. This free electrons carry electric current from one place to another place. At zener breakdown region, a small increase in voltage will rapidly increases the electric current.

- Zener breakdown occurs at low reverse voltage whereas avalanche breakdown occurs at high reverse voltage.
- Zener breakdown occurs in zener diodes because they have very thin depletion region.
- Breakdown region is the normal operating region for a zener diode.
- Zener breakdown occurs in zener diodes with zener voltage (V_z) less than 6V.

Symbol of zener diode

The symbol of zener diode is shown in below figure. Zener diode consists of two terminals: cathode and anode.



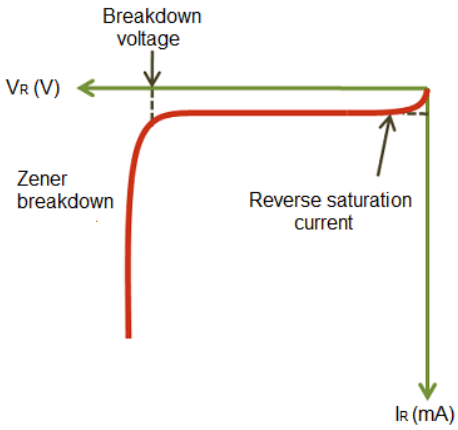
In zener diode, electric current flows from both anode to cathode and cathode to anode.

The symbol of zener diode is similar to the normal p-n junction diode, but with bend edges on the vertical bar.

VI characteristics of zener diode

The VI characteristics of a zener diode is shown in the below figure. When

forward biased voltage is applied to the zener diode, it works like a normal diode. However, when reverse biased voltage is applied to the zener diode, it works in different manner.



When reverse biased voltage is applied to a zener diode, it allows only a small amount of leakage current until the voltage is less than zener voltage. When reverse biased voltage applied to the zener diode reaches zener voltage, it starts allowing large amount of electric current. At this point, a small increase in reverse voltage will rapidly increases the electric current. Because of this sudden rise in electric current, breakdown occurs called zener breakdown. However, zener diode exhibits a controlled breakdown that does damage the device.

The zener breakdown voltage of the zener diode is depends on the amount of doping applied. If the diode is heavily doped, zener breakdown occurs at low reverse voltages. On the other hand, if the diode is lightly doped, the zener breakdown occurs at high reverse voltages. Zener diodes are available with zener voltages in the range of 1.8V to 400V.

Advantages of zener diode

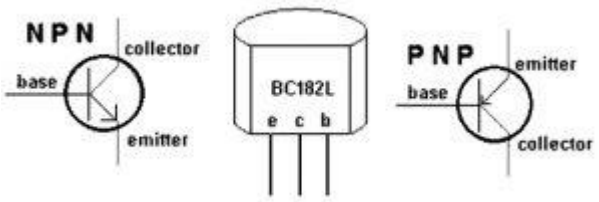
- Power dissipation capacity is very high
- High accuracy
- Small size
- Low cost

Applications of zener diode

- It is normally used as voltage reference
- Zener diodes are used in voltage stabilizers or shunt regulators.
- Zener diodes are used in switching operations
- Zener diodes are used in clipping and clamping circuits.
- Zener diodes are used in various protection circuits

2.6 BJT

The Bipolar junction transistor is a solid-state device and, in these transistors, the current flow in two terminals are emitter and collector, and the flow of current controlled by the third terminal is the base terminal. It is different from the other type of transistor, i.e. Field-effect transistor which is the output current is controlled by the input voltage. The basic symbol of the BJTs n-type and p-type is shown below.



BJT or Bipolar Junction Transistor Symbol

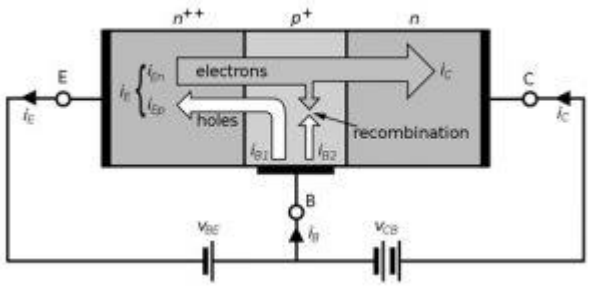
Why BJT is Called Bipolar?

A BJT is a 3-terminal semiconductor device, as the name suggests, the term bipolar is taken from the truth that this kind of transistor includes two kinds of semiconductor materials like P-type (positive type) and n-type (negative type) where the current flows from these regions Usually, these transistors include Silicon.

Construction of Bipolar Junction Transistor

The construction of BJT will determine its working characteristics. So, the construction of BJT can be done through three doped semiconductor sections

which are separated through two PN-junctions. This transistor includes three layers namely base, emitter, and collector. These transistors are available in two types namely PNP and NPN and their physical structure is shown below.



Construction of Bipolar Junction Transistor

In NPN, it includes two N-regions separated by one P-region whereas, in PNP, it includes two P-regions and separates with one N-region. In BJT, the term bipolar refers to the utilization of both the charge carriers like electrons and holes within the structure.

When PN-junction connects the base and emitter region then it is known as BE-junction. Similarly, once the pn-junction connects the base & the collector region then it is known as the BC-junction. A wire lead unites to every region and these leads are branded with C, B & E for the collector, base, and emitter respectively.

The base (B) – region is slightly doped & it is extremely thin as compared to the emitter terminal that is heavily doped & the somewhat doped collector region. The schematic symbols of the NPN and PNP BJTs include the following.

Terminals of BJT

The BJT includes three terminals like base, Emitter, and Collector which are discussed in brief. The NPN and PNP transistors symbol representation can be done like the following. The arrow symbol on the emitter terminal is always there and the arrow direction will represent the current flow because of the

charge carriers.

Emitter Terminal

The emitter terminal emits the charge carriers like holes or electrons to the other two terminals. The base terminal is always reverse biased with respect to other terminals like emitter so that it can produce huge majority carriers. In BJT, the emitter is the most heavily doped region.

The emitter-base junction must be connected in forwarding bias within both the transistors like PNP & NPN. The emitter terminal provides electrons toward the EB-junction within NPN transistor whereas it supplies charge carriers like holes to the same junction within the PNP transistor.

Collector Terminal

The part on the reverse side of the Emitter terminal will collect the emitted charge carriers called a collector. So, this terminal is heavily doped however the doping level of this terminal is among the base terminal which is a lightly doped & heavily doped emitter terminal. CB-junction must be reversely biased in both the transistors.

The main reason for this biasing is to eliminate charge carriers from the CB-junction. The collector terminal of the NPN transistor is to collects electrons that are emitted through the emitter terminal whereas, in the PNP transistor, it gathers holes that are emitted through the emitter terminal.

Base Terminal

The base terminal is the center part among collector & emitter terminals which forms two PN junctions among them. The base terminal is the most lightly doped segment in the transistor. So, being the central part of the BJT will allow it to manage the charge carriers flow among emitter & collector terminals. The

BE junction shows high resistance as this junction can be connected in reversed bias.

Working of BJT

Bipolar junction transistor is classified into two types namely PNP and NPN based on types of doping of the terminals. In NPN transistor, two semiconductor junctions are there which have a thin anode region doped with 'P' whereas PNP transistor includes two semiconductor junctions that include a thin cathode region doped with 'N'.

The flow of charge within a transistor is because of the charge carrier's diffusion among the two sections which belongs to different concentrations of charge carriers. The emitter section is doped highly as compared to the remaining layers.

Both the layers like base and collector include the same concentrations of charge carriers. So, between these three junctions, the BE junction can be connected in forwarding bias & the BC junction is reverse biased. The operating of BJT can be done in three different regions like active, saturation, and cut-off.

Active Region

In this region, one junction is connected in a forward bias whereas the other one is connected in reverse bias. Here, the base current (Ib) is used to control the quantity of Ic (collector current). So, the active region can be mainly used for the purpose of amplification wherever this transistor performs like an amplifier through a gain 'β' with the following equation;

$$\mathbf{Ic = \beta \times Ib}$$

The active region is also called a linear region which lies in between the two regions like the cutoff & the saturation. The typical operation of this transistor happens within this region.

Saturation Region

In this region, the transistors both the junctions are connected in forwarding bias. So this region is mainly used for the ON-state for a switch wherever;

$$\mathbf{Ic = Isat}$$

Here, 'Isat' is the saturation current and it is the highest quantity of current flow among the two terminals like emitter as well as collector once this transistor is connected in the saturation region. As these junctions are connected in forwarding bias then the transistor works like a short circuit.

Cutoff Region

In this region, both the transistor junctions are connected in reverse bias. Here this transistor works like the off condition of a switch wherever

$$\mathbf{Ic = 0}$$

In the cut-off region, the operation is totally reverse as compared to the saturation region. So, there are no exterior supplies connected. If there is no collector current then there is no emitter current.

In this method, the transistor works like an off-state of the switch, and this mode can be achieved by decreasing base voltage to below the voltage of both the emitter as well as collector. Vbe< 0.7

Types of Bipolar Junction Transistor

As we have seen a semiconductor offer less resistance to flow current in one direction and high resistance is another direction and we can call transistor as the device mode of the semiconductor. The Bipolar junction transistor consists of two types of transistors. Which, given us

- Point contact
- Junction transistor

By comparing two transistors the junction transistors are used more than point type transistors. Further, the junction transistors are classified into two types

which are given below. There are three electrodes for each junction transistor they are emitter, collector, and base

- PNP junction transistors
- NPN junction transistors

PNP Junction Transistor

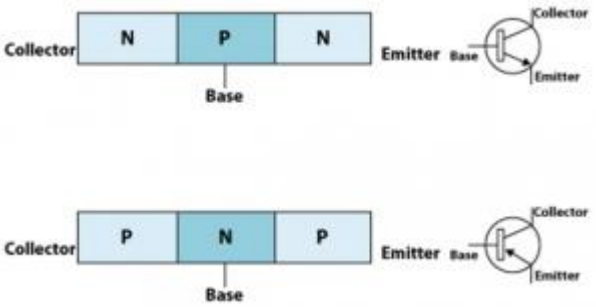
In the PNP transistors, the emitter is more positive with the base and also with respect to the collector. The PNP transistor is a three-terminal device that is made from semiconductor material. The three terminals are collector, base, and emitter, and the transistor is used for switching and amplifying applications. The operation of the PNP transistor is shown below.

Generally, the collector terminal is connected to the positive terminal and the emitter to a negative supply with a resistor either the emitter or collector circuit. To the base terminal, the voltage is applied and it operates transistor as an ON/OFF state. The transistor is in the OFF state when the base voltage is the same as the emitter voltage. The transistor mode is in ON state when the base voltage decreases with respect to the emitter. By using this property the transistor can act on both applications like switch and amplifier. The basic diagram of the PNP transistor is shown below.

NPN Junction Transistor

The NPN transistor is exactly opposite to the PNP transistor. The NPN transistor contains three terminals which are the same as the PNP transistor which are emitter, collector, and base. The operation of the NPN transistor is generally, the positive supply is given to the collector terminal and the negative supply to the emitter terminal with a resistor either the emitter or collector or emitter circuit. To the base terminal, the voltage is applied and it operated as an ONN/OFF state of a transistor. The transistor is in an OFF state when the base voltage is the same as the emitter. If the base voltage is increased with respect to the emitter

then the transistor mode is in an ON state. By using this condition the transistor can act like both applications which are amplifier and switch. The basic symbol and the NPN configuration diagram as shown below.



PNP & NPN Bipolar Junction Transistor

Hetero Bipolar Junction

The Hetero bipolar junction transistor is also a type is the bipolar junction transistor. It uses different semiconductor materials to the emitter and base region and produces heterojunction. The HBT can handle the singles of very high frequencies of several hundred GHz generally it is used in ultrafast circuits and mostly used in radiofrequency. Its applications are used in cellular phones, and RF power amplifiers.

Working Principle of BJT

The BE junction is forward bias and the CB is a reverse bias junction. The width of the depletion region of the CB junction is higher than the BE junction. The forward bias at the BE junction decreases the barrier potential and produces electrons to flow from the emitter to the base.

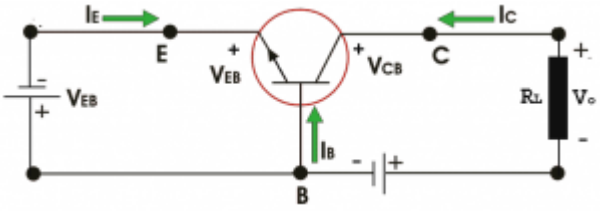
The base is thin and lightly doped, it has very few holes and less amount of electrons from the emitter about 2% it recombine in the base region with holes, and from the base terminal it will flow out. This initiates the base current flow due to the combination of electrons and holes. The leftover large number of electrons will pass the reverse bias collector junction to initiate the collector current. By using KCL we can observe the mathematical equation

$$I_E = I_B + I_C$$

The base current is very less as compared to emitter and collector current

$$I_E \sim I_C$$

Here the operation of the PNP transistor is the same as the NPN transistor the only difference is only holes instead of electrons. The below diagram shows the PNP transistor of the active mode region.



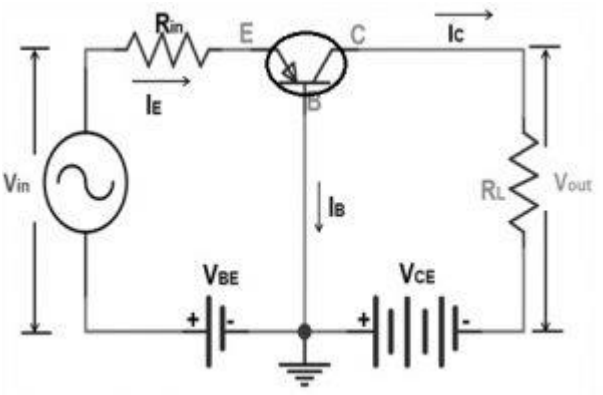
Working Principle of BJT

BJT Configuration

A bipolar junction transistor includes a three-terminal device so it can be connected to a circuit in three possible ways through one terminal being common between others which means one terminal in between input as well as output is common. Every connection simply responds in a different way to the input signal.

Common Base Configuration

In the CB configuration of the transistor, the base terminal is common among the input & output signals. Here, the input signal can be given among the two terminals like base as well as emitter whereas the output can be obtained among the two terminals like base & collector. At the collector terminal, the output signal is low as compared to the input signal at the emitter terminal.



CB Configuration

Thus, its gain is less than 1, so, it attenuates the signal. This output of this configuration is non-inverting, so both inputs, as well as output signals, will be in phase. This common base configuration is not commonly used due to its high voltage gain. Because of its extremely high-frequency response, this kind of configuration is used only for 1- phase amplifier. These 1-phase amplifiers can be used like RF amplifiers and microphone pre-amplifier.

Gains of CB Configuration

Voltage Gain = **Av = Vout/Vin = Ic x RL/IE X RIN**

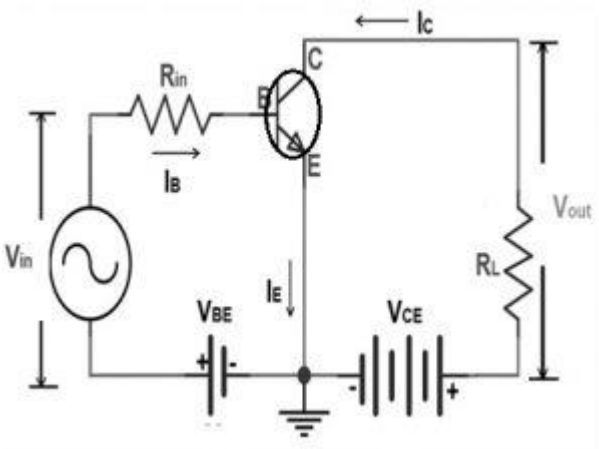
Current Gain = **Ic/ie**

Resistance Gain = **RL/Rin**

Common Emitter Configuration

In this configuration, the emitter terminal is common among input & output. The input is given among the two terminals like base and emitter whereas the output can be obtained among collector and emitter terminals.

It can be simply identified through observing the circuit. When the emitter terminal is connected to GND then input & output are obtained from the base & collector terminals respectively. The CE configuration includes the maximum current & power gain between all types of configurations.



CE Configuration

The main reason is because of the input at the junction of forwarding bias, so its input impedance is extremely less whereas the output can be received from reverse bias junction. Thus, its output impedance is extremely high. In CE configuration, the emitter current is equivalent to the amount of base & collector currents. So the equation is

Ie= Ic + Ib

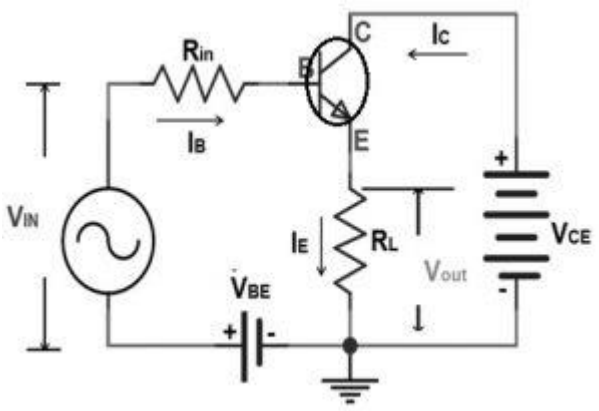
From the above equation, 'Ie' is the emitter current. So, this configuration has maximum current gain like Ic/Ib because the load resistance can be connected within series through the collector terminal.

It can be observed from the above equation that a small increase within the base current will effect in very high current at the output region.

This CE configuration works like an inverting amplifier wherever the output signal is totally opposite within polarity toward the input signal. Thus, the output signal can be shifted at 180° with respect to its input signal.

Common Collector Configuration

The CC configuration is also called an emitter follower or voltage follower that includes a collector which is grounded. In CC configuration, the connection of the collector terminal can be done to ground toward the supply.



CC Configuration

For both input & output, the collector terminal is common. The output is obtained from the emitter through load which is connected in series whereas the input is provided toward the base terminal directly. This configuration includes high input as well as output impedance.

This permits it to execute like an impedance matcher. Thus this kind of configuration is extremely useful within the impedance matching method.

BJT Characteristics

The behavior of the bipolar transistor in every circuit configuration is extremely different & generates dissimilar circuit characteristics with respect to input & output impedances and gains like the voltage, power, and current. The fixed characteristics of a BJT can be separated into three main groups which are mentioned below.

Input Characteristics

Common base (CB) = ΔVEB / ΔIE

Common Emitter (CE) = ΔVBE / ΔIB

Output Characteristics

Common Base (CB) = ΔVC / ΔIC

Common Emitter (CE) = ΔVC / ΔIC

Transfer Characteristics

Common Base (CB) = ΔIC / ΔIE

Common Emitter (CE) = ΔIC / ΔIB

The different transistor configuration characteristics are given below.

Characteristics	CB	CE	CC
Input Impedance	Low	Medium	High
Output Impedance	Very High	Low	Low
Phase Angle	0^o	180^o	0^o
Voltage Gain	High	Medium	Low
Current Gain	Low	Medium	High
Power Gain	Low	Very High	Medium

Advantages of BJT

The main **advantages of bipolar junction transistors** include the following.

- High driving capability
- High-frequency operation
- The digital logic family has an emitter-coupled logic used in BJTs as a digital switch
- It has a high gain bandwidth
- It gives good performance at high frequency
- Voltage gain is good
- It operates in low power or high-power applications
- It includes maximum current density.
- Forward voltage drop is low

Disadvantages

The main **disadvantages of bipolar junction transistors** include the following.

- Thermal stability is less
- It generates more noise
- The BJT is more an effect of radiation.
- Less switching frequency

- Base control is complex so needs skillful handling.
- The time taken for switching is not fast as compared to a high flashing frequency of voltage & current.

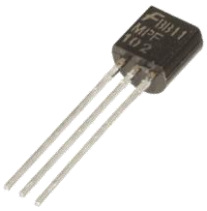
Applications of BJT

Following are the two different types of applications in BJT they are

- Switching
- Amplification
- Converters
- Automatic switch
- Temperature sensors
- Electronic switches
- Amplifiers
- High driving capability
- Detection circuits
- High-frequency operation
- Demodulator and modulator
- Digital switch
- Clippers
- Oscillation circuit

2.7 JFET

JFET consist of the channel of semiconducting material through which a current flows. Jfet's are of two types; one is n-channel JFET and another is p-channel JFET. Generally, n-channel JFET are more preferred than p-channel JFET because in n-channel electrons are the majority carriers and as we know electrons are more mobile than holes.



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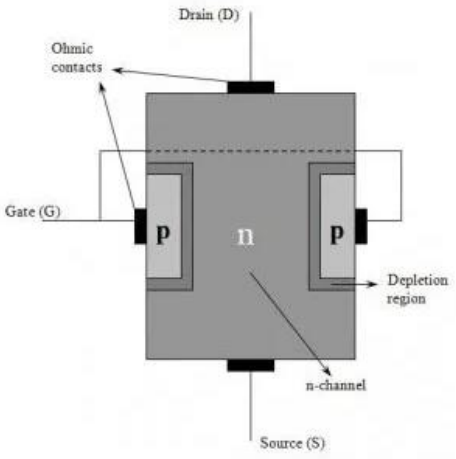
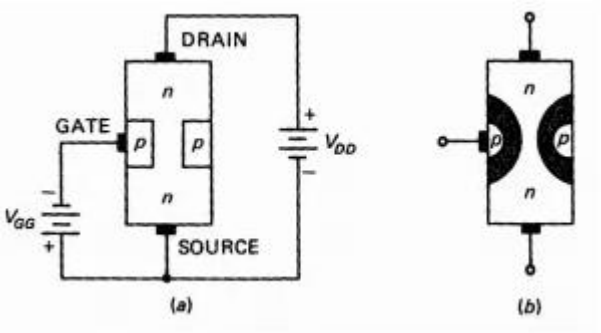


In an N-channel JFET, two smaller pieces of p-type silicon material diffused on the opposite sides of its middle part forming p- n junction and an n-type silicon bar considered as the channel. Similarly in p-channel JFET, smaller pieces of n-type silicon material diffused on the opposite sides of its middle part forming p-n junction and a p-type silicon bar considered as the channel The two p-n junction forms diodes or gates internally known as a gate terminal. By using battery make ohmic contacts at the two ends of the channel- one is called source terminal and other is called Drain terminal. Gate terminal is used to control the flow of current from source to Drain. Gate-source forms one p-n junction diode while Drain forms another p-n junction diode. These diodes are known as the gate -source diode and gate- drain diode.

JFET operation

Both N-channel JFET and p-channel JFET operated in the same way, although the charge carriers are inverted i.e. electrons are majority carriers in n-channel and holes are majority carriers in p-channel. Here we explain n-channel jfet operation because it is more preferable. The width of the channel varies in accordance with the magnitude of the bias applied to the gate terminal and source-drain terminal. As shown in the figure above we explain how channel width change when we apply either a positive voltage or negative across it. Let's have a detailed look at it.



JFET operates in three conditions depending upon the voltage applied across terminals:

(i) No voltage: When neither any voltage is applied across source to drain terminal i.e.Vds = 0 nor any bias is applied to the gate terminal i.e. Vgs= 0, the depletion region around the p-n junction are of equal thickness and symmetrical in nature.

(ii) Negative Voltage: When the gate is negative bias with respect to the source and drain is applied with a positive bias with respect to the source, the p-n junction got reverse biased and forms depletion region. When the drain current flows through the channel, there is a voltage drop along its length. The result is that the reverse bias at the drain end is more than that at the source end making the width of depletion layer more at the drain. With the increasing resistance and

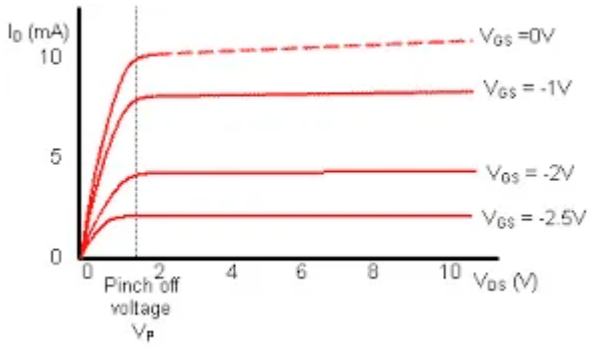
reducing current Id , the channel starts narrowing. If we further increase the negative voltage across the gate, depletion layers meet at the centre and the drain current cut off completely. Similarly, if we reduce the negative voltage across the gate, the depletion layers start reducing causing decrease in resistance and increase in drain current Id.

(iii) Positive voltage: When a positive voltage is applied to the drain terminal with respect to source terminal without connecting the gate terminal to the supply, the electrons starts moving from source terminal to drain terminal whereas conventional drain current Id flows through the channel from Drain to the source. Due to this flow of current, the uniform voltage drop occurs across the channel resistance which reverse bias the diode. The gate is more negative to those points in the channel which are nearer to drain than the source. Therefore, depletion layers penetrate more deeply into the channel at points which are more closer to drain than the source. As a result, the wedge-shaped depletion regions are formed when Vds is applied across the terminals.

Characteristics of JFET

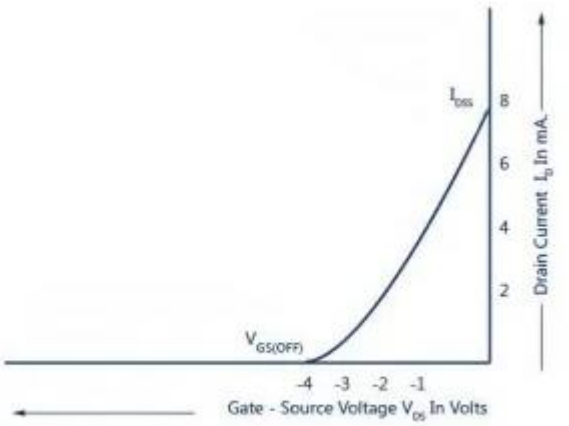
The characteristic curve indicates the behavior of the device by increasing or decreasing current and voltages applied across their terminals. There are two types of static characteristics of JFET are:

(i) Output or Drain characteristics:



The curve drawn between drain current Id and drain-source voltage VDS along y-axis and x-axis with gate to source voltage Vgs as the parameter is called the drain or output characteristic. As shown in the figure below, the curves are very nearly horizontal at voltages greater than the pinch-off voltage.

(ii) Transfer characteristics: By keeping the drain-source voltage constant VDS and finding the drain current Id for various values of gate-source voltage Vgs,the transfer characteristics can be determined experimentally.



Transfer Characteristics of JFET

As shown in the figure above, we observe the following things from its curves are:

- When Vgs = 0 then Drain current Id = Idss
- When Vgs = Vd then Drain current Id = 0
- Drain current decreases with an increase in negative gate-source bias.

Applications of Junction Field Effect Transistor

JFET Junction Field effect transistor is widely used in various applications because of its extraordinary features.

Following are:

- Voltage-controlled Resistor
- Differential Amplifier
- Constant current source
- Low noise Amplifier
- High input impedance Amplifier
- Analog Switch or gate

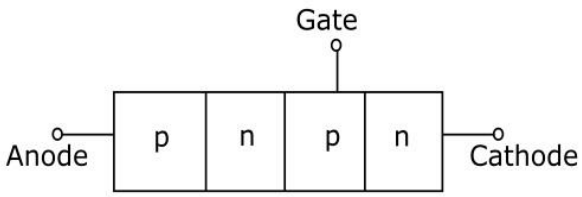
2.8 SCR

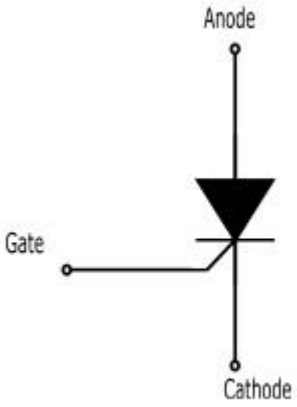
An SCR is a three-terminal, three-junction, and four-layer semiconductor device that is used to perform switching functions in power circuits.

Sometimes the SCR is also called as Thyristor.

Constructional Details of SCR

The SCR has three pn – junctions, and four layer of p and n type semiconductor joined alternatively to get pnpn device. The three terminals are taken – one from outer p – type layer called anode (A), second from the outer n – type layer called cathode (K) and the third from the internal p –type layer called gate (G).



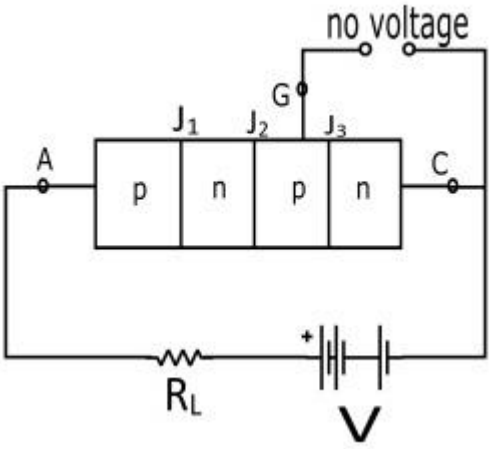


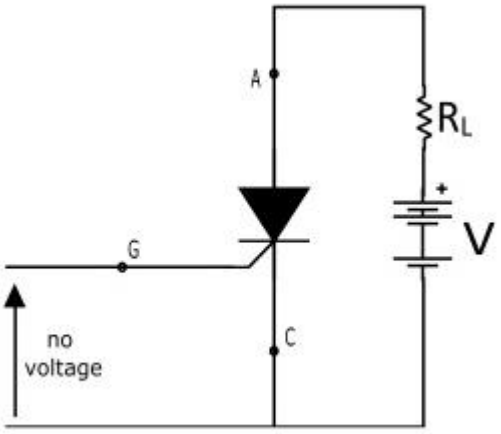
Working of SCR

In a SCR, the load is connected in series with the anode. The anode is always kept positive with respect to cathode.

When Gate is Open Circuited

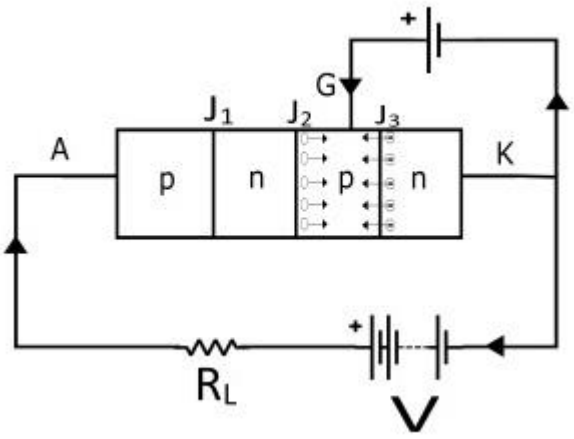
When no voltage applied to gate terminal, junction J2, is reverse biased and the junctions J1 and J3 are forward biased. Since one of the three junctions is reverse biased so there is no current can flow through the load, hence the SCR is OFF. However if the applied voltage is gradually increased, a stage is reached, when reverse biased junction (J2) breaks down. The SCR now, starts conducting and become ON. The value of applied voltage at which the reverse biased junction breaks down and the SCR becomes ON is known as Breakover Voltage.

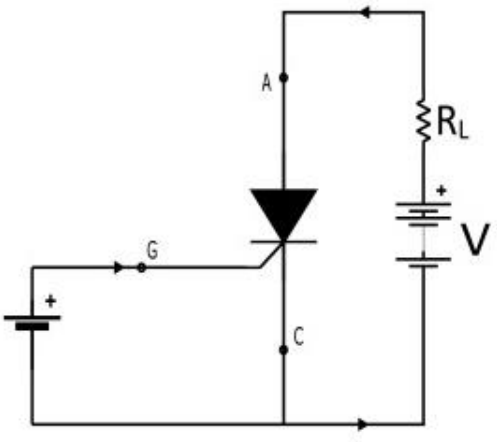




When Gate is Positive with Respect to Cathode

The SCR can be turned ON at smaller applied voltage by the application of a small positive voltage at the gate terminal. When gate voltage is applied the junction J3 is forward biased and junction J2 is reverse biased. Thus, the electrons from n – type layer starts moving across the junction J3 toward p –type material and the holes from p –type material towards the n – type material. Due to the movement of holes and electrons across the junction J3 the gate current starts flowing. Because of gate current the anode current increases. The increased anode current makes the more electrons available at the junction J2. As a result of this process, in a small time, the junction J2 breaks down and the SCR is turn ON.





Even if the voltage at the gate terminal is removed, the SCR the anode current does not decrease. The SCR can only be turned off by reducing the applied voltage to zero.

Parameters of SCR

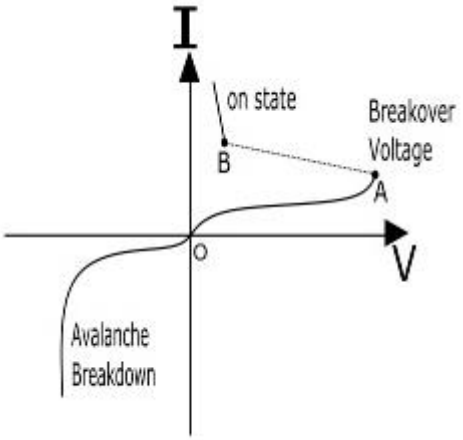
- **Break Over Voltage** − It is the minimum value of the applied voltage at which the SCR is turned ON, provided the gate voltage is not applied. For commercially available SCRs the range of break over voltage is 50 V to 500 V.
- **Peak Reverse Voltage (PRV)** − It is the maximum reverse voltage (i.e. cathode made positive with respect to the anode) that can be applied to the SCR without conducting in the reverse direction. The commercially available SCRs have PRV up to 2.5 kV.
- **Holding Current** − With gate being open, it is the maximum value of anode current at which SCR is turned OFF from ON state.
- **Forward Current Rating** − It is maximum value of the anode current that an SCR can pass through it without destruction.
- **Circuit Fusing Rating** − It indicates the maximum forward surge current capability of the SCR. It is defined as the product of square of forward surge current and the time duration of the surge.

If the circuit fusing rating is exceeded in the SCR circuit, the device is destroyed by excessive power dissipation.

$$\text{CircuitFusingRating}=I^2t$$

I–V Characteristics of SCR

It is the curve plotted between the anode – cathode voltage (V) and anode current (I) of the SCR at constant gate current.



- **Forward Characteristics** − When the anode is made positive with respect to the cathode, then the curve between V and I is called as forward characteristics of the SCR. If the supply voltage is increased from zero, a point is reached (Point A, the voltage is called breakover voltage) when the SCR starts conducting. Under this condition, the voltage across SCR decreases suddenly (shown by dotted line in the curve) and the most of the supply voltage appears across the load.

- **Reverse Characteristics** − When anode is made negative with respect to the cathode, the curve plotted between V and I is called as reverse characteristics. If the reverse voltage is increased gradually, at first the anode current remains small (called leakage current) and at some reverse voltage, the avalanche breakdown occurs and the SCR starts conducting in the reverse direction (Shown by the curve in third quadrant). The maximum reverse voltage at which the SCR starts conducting in the reverse direction is called as Reverse Breakdown Voltage.

Applications of SCR

The SCR can be used in following application −

- Power Switching Circuit
- Controlled Rectifier
- AC power control circuits
- Speed control of DC shunt motor
- SCR Crowbar
- Computer logic circuits
- Timing Circuits
- Inverters
- Battery Charging Regulators
- Temperature control systems

2.9 MOSFET

MOSFET is a metal oxide semiconductor that is under the category of the field-effect transistor (FET). These transistors are widely used under the varieties of the applications relating to the amplification and the switching of the devices. Because of its fabrication MOSFET's are available in smaller sizes. It consists of a source, drain, gate and the substrate of the transistor as its terminals. For the circuitry of analog or it be digital this one is the widely preferred transistor. Based on the variation at the depletion region width and the flow of the majority concentration of the carriers the working of the MOSFET is classified as depletion type and enhancement type.

A FET that is designed with the gate terminal being insulted from the substrate which is either the p-type or n-type material is called as **Metal Oxide Semiconductor Field Effect Transistor**. The Gate terminal which is a metal piece is insulated by material like silicon dioxide(Si02). The working of these MOSFETs depends upon the conduction of the charges through the channels based on the gate-source voltage.

Types of MOSFETs

Firstly based on the types of the channel it is classified as **p-channel** or **n-channel** MOSFETs. The presence of the channel in the transistor makes the MOSFET to operate into two different modes. If the channel exists and once the biasing is provided it starts to conduct then it is referred to as **Depletion mode**. Due to the biasing if the channel is created and then the conduction began then it is this referred to as **Enhancement mode**.

(1) Enhancement Mode

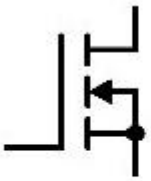
The application of the voltage makes the device to turn into ON mode known as Enhancement Mode. Generally, it is known for the characteristics similar to that of an open switch.

(2) Depletion Mode

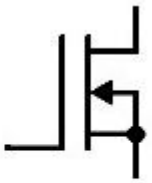
In this mode, the application of the voltage makes the device turn into OFF mode. Hence these mode characteristics are equivalent to the closed switch.

MOSFET Symbol

The symbol of the MOSFET consists of the terminals and the representation of the channels based on the condition of the biasing and the way channel reacts to it make the device to conduct the flow of the charge carriers. The direction of the arrow in the below symbols represents the direction of the flow of charge carriers. In N- channel type it flows outward towards the gate and in P- channel type it flows inward away from the gate terminal.



MOSFET: N-Channel
Enhancement Type



MOSFET: N-Channel
Depletion Type

Symbols for N-channel Depletion and Enhancement Types

Structure of MOSFET

The structure of the MOSFET is highly dependent on the influence of the majority of the charge carriers. Hence it makes the designing of this type of structure as the quite difficult one in comparison with the structure of the JFET. The formations of the electric field in this MOSFET either enhancement or depletion is completely dependent on the voltage applied at the terminal gate which in turn depends on the channel . If it is p-channel the majority of the concentration of the carriers will be holes and for n-type the majority of the concentration of the carriers are electrons.

Based on the biasing applied at the terminal gate the transistor conducts. If there is no conducting voltage provided then, in that case, it will remain in non-conducting mode. So these are generally preferred in switching the devices because it makes the device to turn ON or OFF based on the biasing.

Threshold Voltage

The voltage that is applied between the gate and the source terminal upon which the device turns on or off is called threshold voltage and it is also referred to as the gate voltage.

MOSFET Working

MOSFET working is highly dependent on the channel present in between the terminals. The presence of a p-type channel makes the transistor conduction possible due to its majority charge carriers referred to as holes. In the n-type channel, the transistor conductivity is based on their majority charge concentrations that are known as electrons.

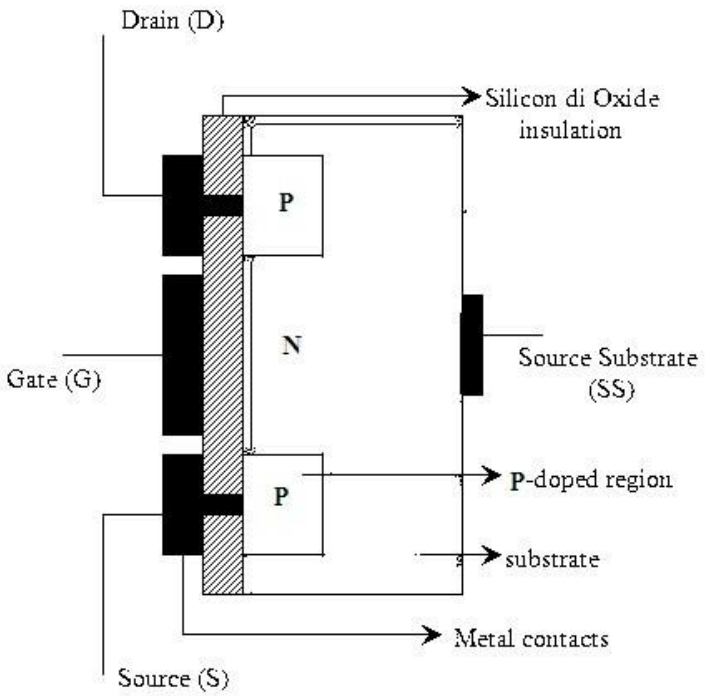
(1) P-Channel

In this type of MOSFET, the source and drain are highly doped with a p-type material and they have very lightly doped n-type substrate. When the space

between the drain and source are doped with a p-type impurities which becomes a channel between the source and the drain then it is a P-type depletion mode MOSFET and if the channel is formed between drain and source by the application of the gate voltage then it is P-type enhancement mode MOSFET.

P-Channel Enhancement Mode Working

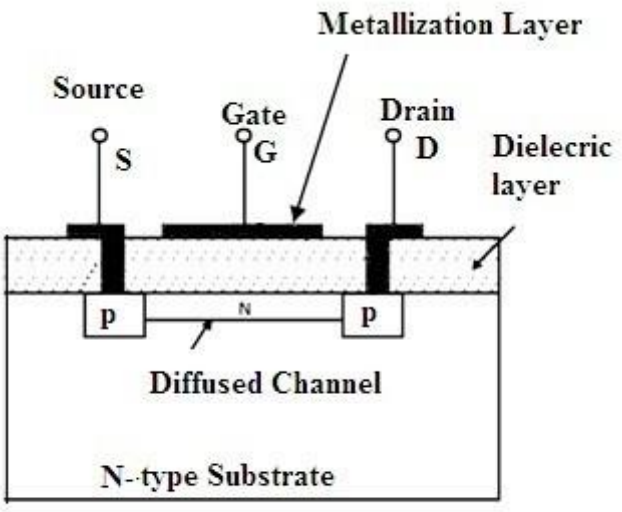
Here the device starts conducting when a negative voltage is applied to the Gate terminal. When a negative voltage is applied to all the holes which are minority carriers in the n-type moves toward the gate terminal. But on its way, some of them combine with the some of the electrons which are minority carriers in the p-type drain and source. But at a particular voltage known as the **threshold voltage,** the holes will be able to overcome the recombination resulting in the formation of the channel between the drain and the source. Under this condition when a negative voltage is applied to the drain terminal the device starts conducting. Since the channel formed here is of holes it is called as **P-channel Enhancement MOSFET**.



P-Channel Enhancement MOSFET

P-Channel Depletion Mode Working

In this Mode when the gate voltage is zero and when a negative voltage is applied between the drain and the source then the holes start moving towards the drain because of the negative voltage and the device starts conducting. When a positive voltage is applied to the Gate terminal then the holes in the p channel get pushed toward the N-type substrate and start the recombine with the electrons in the N-type substrate. As the voltage increase, the number of recombination increases and this results in the depletion of the charge carriers(holes) which results in the reduction of the drain current. At a particular positive voltage of the gate terminal, the device stops conducting this voltage is called the **Pinch-off voltage**. When a negative voltage is applied to the Gate terminal then the holes which are the minority carriers in the n-type substrate moves directly towards the channel, as a result, the Drain current starts increasing. As the negative voltage of the Gate terminal increases the Drain current also increases. This region is called the **Enhancement region.**



P-Channel Depletion MOSFET

The variation in the width of the regions impacts the conductivity of the

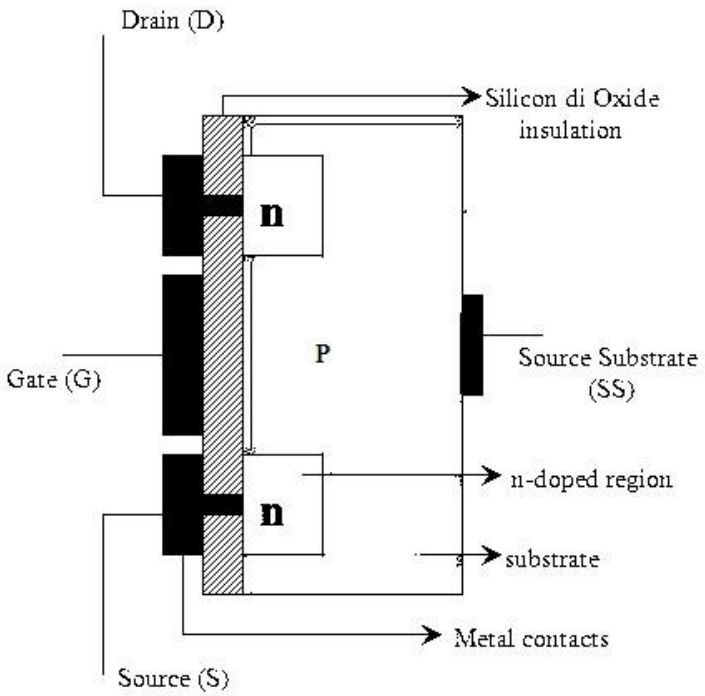
transistor. This is the reason it is known as the depletion type of p-channel MOSFET.

(2) N-Channel

In an N-type MOSFET, the source and the drain have a highly doped N-type material and lightly doped P-type substrate. Based on the way the channel is formed these are also classified as enhancement and the depletion type of MOSFETs.

N-Channel Enhancement Mode Working

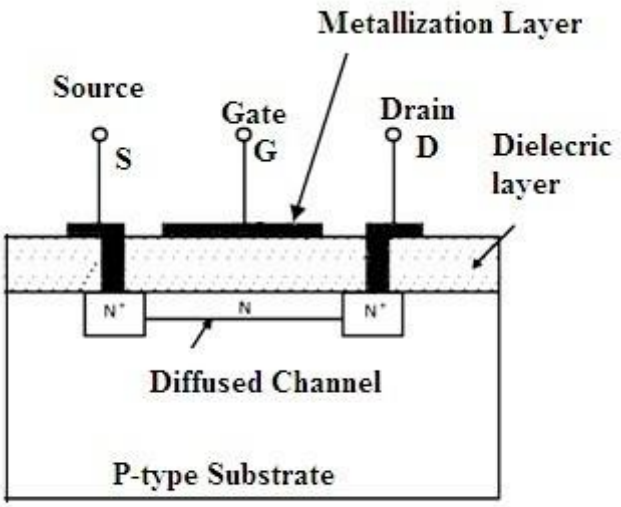
The positive polarity of the voltage is considered here because n-channel consists of the majority of the carriers as electrons. The operation is similar to p-type MOSFET except that the device starts conducting when a positive voltage applied to the gate terminal. As the positive voltage in the gate terminal is increased at a particular **threshold voltage** and a channel gets formed drain and source. Under this condition, if a positive voltage is applied between the drain and source the device starts conducting.



N-Channel Enhancement MOSFET

N-Channel Depletion Mode Working

This mode of operation is similar to the P-type depletion-mode except that the drain to source terminal should be forward biased and a positive voltage should be applied to the Gate terminal for the current to flow from the drain to source. When a negative voltage is applied the major charge carriers get repelled towards the substrate and combines with the electrons resulting in the depletion of the major charge carriers in the channel and so then there will be a reduction in the drain current. At a particular negative voltage, the drain current becomes zero. This voltage is called a **pinch-off voltage.** Hence this type of MOSFET is known as the N-channel Depletion mode MOSFET.



N-Channel Depletion MOSFET

The enhancement mode is known for its characteristics based on the applied voltage whereas depletion is based on the variation of its width of the depletion region.

MOSFET Characteristics

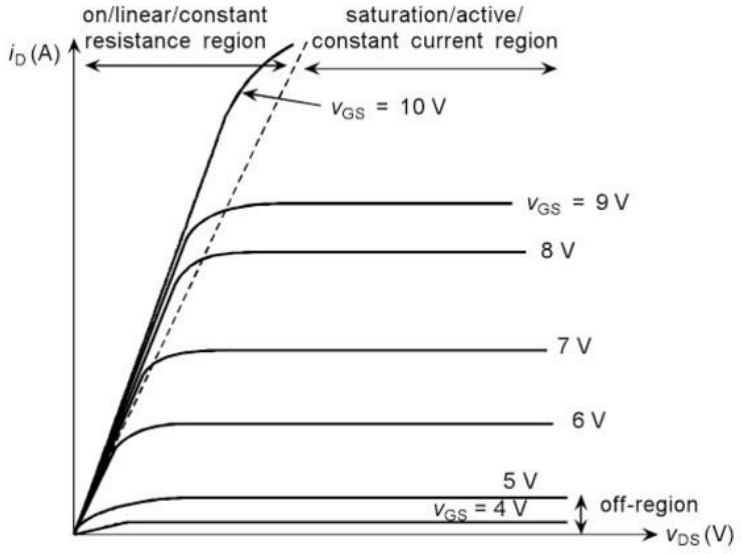
The characteristics of the MOSFET are also dependent on the depletion and the enhancement modes.

Enhancement Mode Characteristics

The most preferred transistor in MOSFET is of enhancement type. In this type, there is no conduction seen if the voltage at the gate and the source terminals are zero. As the voltage reaches the threshold the conductivity tends to increase.

Depletion Mode Characteristics

In this mode, the width of this depletion region is dependent on the applied voltage at the terminal gate. If it is increased in terms of the positive polarity considered then this increment can be seen in the width of the depletion region. This mode of a transistor is very rarely preferred during the design of the electronic circuitry.



I-V Characteristic of N-Channel MOSFET

MOSFET Applications

The applications of the MOSFET are vast in terms of the electronics

(1) The switching consequence of the devices based on the threshold value makes the MOSFET to work as a switch. Based on the channels the polarity of the biasing voltage may vary.

(2) By the application of the pulse-width modulation technique (PWM) the movement of the motors like DC, Stepper, etc… can get controlled.

(3) The amplifiers designed from these devices are used in the systems of the

sounds as well as the radio frequency systems.

(4) The operation of the switching leads to the exploitation of the circuits of the chopper. In this, the value of the DC voltages is converted into the AC voltage by maintaining the same levels for the amplitudes.

(5) If the depletion region of the MOSFET is made in the configuration of the source follower then these circuits are utilized as the voltage regulators in the linear mode.

(6) As the sources that provide the constant value of the current these transistors are utilized.

(7) In order to drive the current or the value of the voltage at a high level, these are preferred in the circuits of oscillators or the mixers.

(8) These are the transistors with the impedance at the high level and possess the switching speed to be at a high level. Because of these characteristics, these are preferred for digital electronics.

(9) It is preferred in various types of systems of sound in the automobiles and the reinforced systems of the sound.

(10) These are preferred in the designing of the calculators.

2.10 IGBT

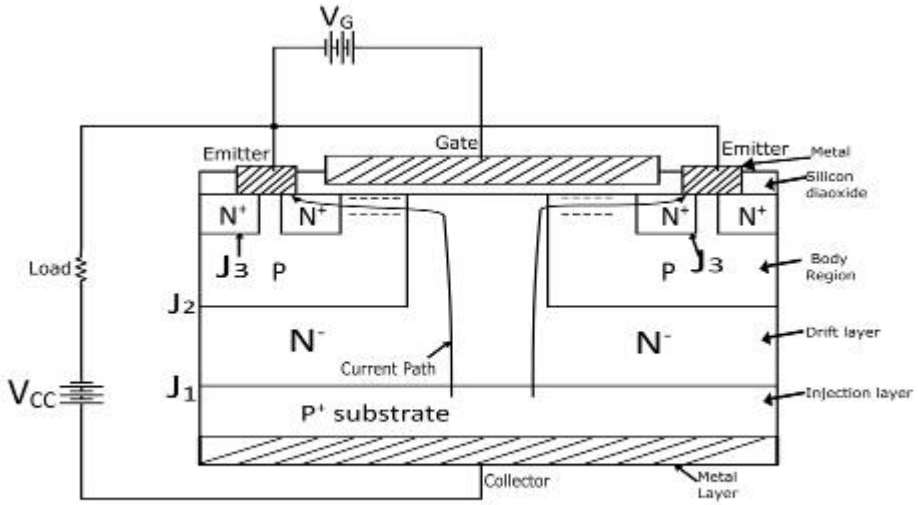
The **Insulated Gate Bipolar Transistor (IGBT)** is a semiconductor device having three terminals – Gate (G), Emitter (E), and Collector (C). IGBT has been developed by combining the best qualities of both BJT and Power MOSFET. Hence, an IGBT exhibits high input impedance as a PMOSFET and has low ON-state power losses like a BJT.

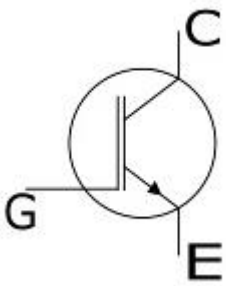
The IGBT is also free from the second breakdown problem that present in the BJT.

IGBT is also known as Insulated Gate Transistor (IGT), Metal Oxide Insulated Gate Transistor (MOSIGT), Conductively Modulated Field Effect Transistor (COMFET) or Gain Modulated FET (GEMFET).

Basic Structure and Schematic Symbol of IGBT

The IGBT is constructed by a p+ layer substrate from the collector. In the IGBT, the p+ substrate is called the **injection layer** since it injects holes into the N- layer (in between the P+ layer and P layer) is called drift region. The thickness of N- layer determines the voltage blocking capability of the IGBT. The P-layer is known as the body region of the IGBT and the body region serves to accommodate depletion of junction J2.





Working of IGBT

When collector is made positive with respect to the emitter, the IGBT is forward biased. When voltage is not applied between gate and emitter, the junction J2 between N- region and P region is reverse biased, hence no current flows from collector to emitter.

When gate is applied with positive voltage with respect to emitter by source VG,

with gate-emitter voltage greater than threshold voltage (V_{GET}) of the IGBT, then an n-channel or inversion layer is induced in the upper part of p-region just below the gate. This n-channel short circuits the N--region with the N+-emitter regions.

Electrons start to flow from N+ region to N- region through the n-channel. Since the IGBT is forward biased, hence the P+ collector region injects holes into the N- drift region, so that the injection carrier density in the N- drift region increases extensively and in turn, the conductivity of N- region increases significantly. Hence the IGBT gets turned ON and starts to conduct forward collector current IC.

The collector current (I_C) or emitter current (I_E) consists of two components viz. one is Hole Current (I_h) due to the injected holes and another is Electron Current (I_e) due to injected electrons. Hence,

The collector or load current IC = emitter current $I_C=I_h+I_e$

Since the major component of the collector current is due to the electron current (I_e). Hence,

$$I_C \cong I_E$$

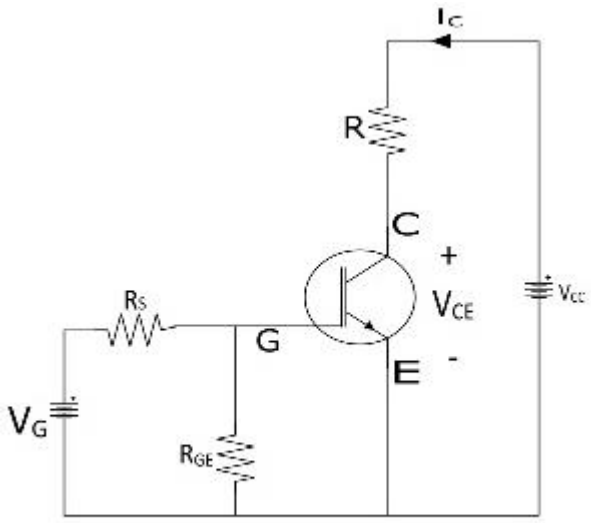
The ON state voltage drop in IGBT is,

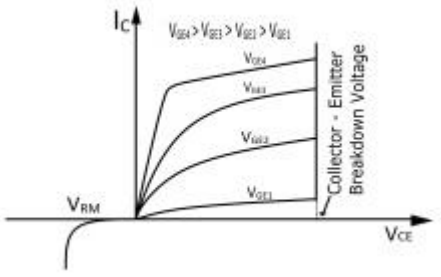
$V_{CE.on}$ = Voltage Drop[in−channel +across drift in N− region +across forward biased P^+ N^- junction J_1]

Output or Static I-V Characteristics of IGBT

The static I-V characteristics or output characteristics of IGBE is the graph between the collector current (I_C) and the collector-emitter voltage (V_{CE}) plotted for various values of gate-emitter voltage.

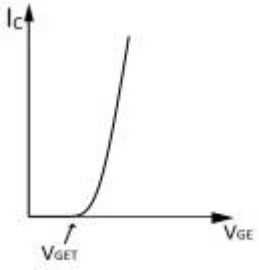
The forward output characteristics is similar to that of BJT. The voltage V_{RM} is the maximum reverse breakdown voltage.





Transfer Characteristics of IGBT

The transfer characteristics of IGBT is the graph between the collector current (I_C) and gate-emitter voltage (V_{GE}). When the value of V_{GE} is smaller than threshold voltage (V_{GET}), the IGBT remains in the OFF state.



Advantages of IGBT

- Lower gate-driver requirements
- Lower switching losses
- Smaller snubber circuit requirement
- Less size and cost
- High efficiency

Applications of IGBT

- IGBT are used in dc and ac motor drives
- Used in UPS systems
- Used in power supplies and drivers for solenoids, relays and contactors

Chapter 3
Rectifiers, Filters and Regulators

Half Wave Rectifier – Ripple Factor – Full Wave Rectifier – Harmonic Components in a Rectifier Circuit – Inductor Filter – Capacitor Filter – Simple Circuit of a Regulator using Zener Diode – Series and Shunt Voltage regulators – Study of Clippers – Clampers – Voltage Multipliers

3.1 Introduction

Rectifiers, filters, and regulators are electronic circuits used in power supplies to convert and regulate electrical power.

Rectifiers are circuits that convert AC (alternating current) voltage into DC (direct current) voltage. They do this by allowing current to flow in only one direction, using a diode or a group of diodes. There are two types of rectifiers: half-wave rectifiers, which use only one diode, and full-wave rectifiers, which use four diodes.

Filters are circuits used to smooth out the DC voltage produced by the rectifiers. They remove the unwanted AC component of the rectified voltage, leaving a smoother DC voltage. There are different types of filters, including capacitive filters, inductive filters, and LC filters.

Regulators are circuits used to maintain a constant output voltage, regardless of

changes in input voltage or load current. There are two types of regulators: linear regulators and switching regulators. Linear regulators use a variable resistance to regulate the output voltage, while switching regulators use a switching transistor to regulate the output voltage.

Together, these three circuits form a complete power supply, providing a stable and reliable source of DC power for electronic devices.

3.2 Half Wave Rectifier

The half wave rectifier conducts current only during the positive half cycles of the input supply voltage.

The negative half cycles of the a.c. supply are suppressed. So no current is conducted and hence no voltage appears across the load. So current always flows in one direction (i.e. d.c) through the load.

Circuit Connections of Half wave Rectifier

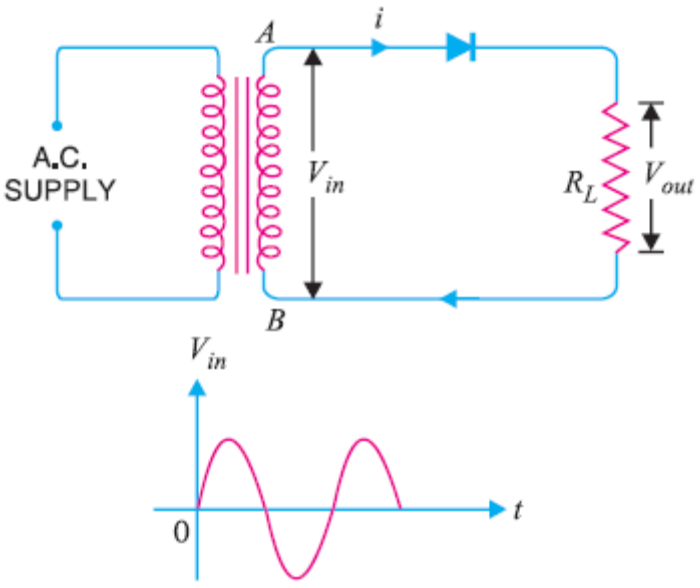


Fig (1) Connection of a half wave rectifier

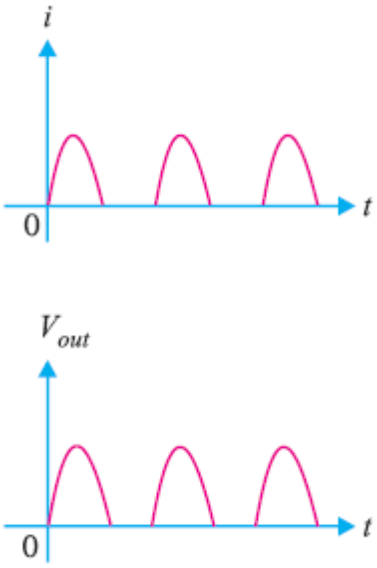


Fig (2) Input and output waveform of a half wave rectifier .

In this circuit a single crystal diode is used as a half wave rectifier .

The a.c. supply is applied in series with the diode D and load resistance R_L

The a.c. supply is normally applied through a transformer. It gives two advantages. First it allows us to step up or step down the a.c. input voltage as required. Secondly, the transformer isolates the rectifier circuit from power line and thus reduces the risk of electric shock.

Operation of Half wave Rectifier

During the positive half cycles of input supply voltage, end A becomes positive with respect to end B.

This makes the diode D forward biased and hence it conducts current.

During negative half cycles, end A becomes negative with respect to end B. So the diode D is reverse biased and hence conducts no current.

So current flows through the diode only during the positive half cycles of the input a.c. voltage.

Hence current flows through the load R_L always in the same direction and d.c. output is obtained across R_L

In half wave rectifier , output across the load is pulsating. So a filter circuit is used to smoothen the output.

Disadvantages of Half Wave Rectifier

The output is pulsating, so a filter circuit is required.

The a.c. supply delivers power only half the time. So output is low.

Output Frequency

The output frequency of a half wave rectifier is equal to the input frequency i.e 50 Hz.

$$f_{out} = f_{in}$$

Efficiency

The ratio of d.c. power output to the applied input a.c. power is known as rectifier efficiency.

Rectifier efficiency

$$\eta = \frac{d.c.power output}{input a.c. power}$$

Let the input supply voltage which appears across the secondary winding

$v = V_m \sin\theta$

Diode resistance = r_f

Load resistance = R_L

The diode conducts only during the positive half cycles of the a.c. supply.

D.C. Power Output

The output current is pulsating direct current.

$I_{av}=I_{dc}$

$$= \frac{1}{2\pi}\int_0^{\pi} id\theta$$

$$= \frac{1}{2\pi}\int_0^{\pi} \frac{V_m sin\theta}{r_f + R_L} d\theta$$

$$= \frac{V_m}{2\pi(r_f + R_L)}\int_0^{\pi} sin\theta d\theta$$

$$= \frac{V_m}{2\pi(r_f + R_L)}[-cos\theta]_0^{\pi}$$

$$= \frac{V_m}{2\pi(r_f + R_L)} \times 2$$

$$= \frac{V_m}{r_f + R_L} \times \frac{1}{\pi}$$

$$= \frac{I_m}{\pi}$$

D.C. power,

$$P_{dc} = {I_{dc}}^2 R_L = \left(\frac{I_m}{\pi}\right)^2 \times R_L = \frac{{I_m}^2 R_L}{\pi^2}$$

A.C. Power input

$$P_{ac} = I_{rms}^{\ 2}(r_f + R_L)$$

$$I_{rms} = \frac{I_m}{2}$$

$$P_{ac} = \left(\frac{I_m}{2}\right)^2 (r_f + R_L)$$

Rectifier Efficiency

$$\eta = \frac{\frac{I_m^{\ 2} R_L}{\pi^2}}{\frac{I_m^{\ 2}(r_f + R_L)}{4}}$$

$$= \frac{0.406 R_L}{r_f + R_L} \quad = \frac{0.406}{1 + \frac{r_f}{R_L}}$$

η will be maximum if r_f is negligible as compared to R_L

Hence maximum efficiency = 40.6%

This means in Half wave rectifier , a maximum of 40.6% of a.c. power is converted into d.c. power.

3.3 Ripple Factor

In half-wave rectification,

$$I_{rms} = \frac{I_m}{2} \; ; \; I_{dc} = \frac{I_m}{\pi}$$

hence,

$$Ripple\ factor = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

$$= \sqrt{\left(\frac{I_m/2}{I_m/\pi}\right)^2 - 1}$$

$$= 1.21$$

Hence it is clear that a.c. component exceeds the d.c. component in the output of a half wave rectifier .It results more pulsation in the output. So half wave rectifier is ineffective for conversion of a.c into d.c.

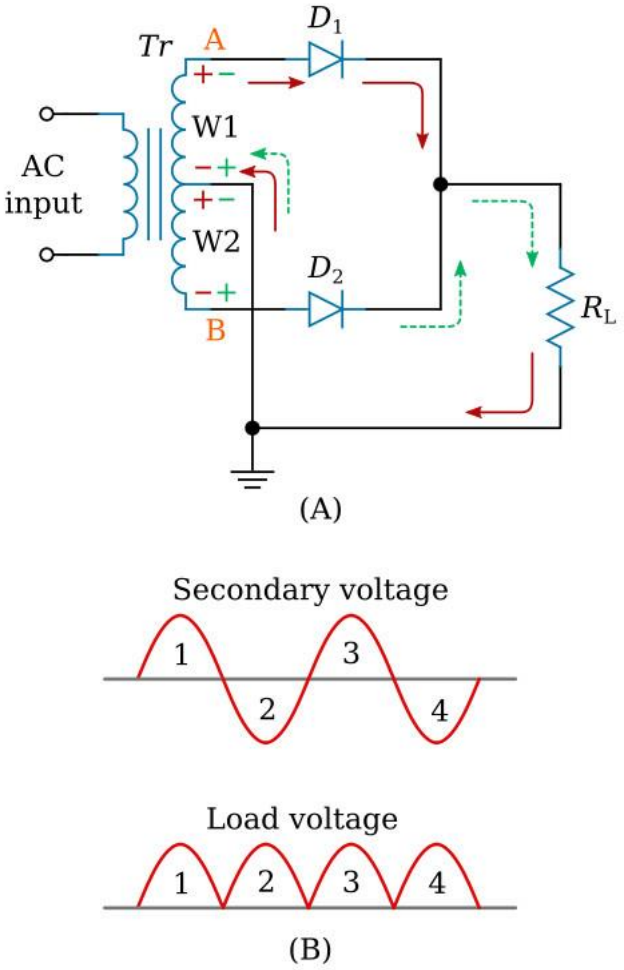
3.4 Full Wave Rectifier

A **full-wave rectifier** is a device that has two or more diodes arranged so that load current flows in the same direction during each half cycle of the AC supply.

The Conventional Full-Wave Rectifier

A diagram of a basic full-wave rectifier is shown in view A of the figure below. The transformer *Tr* supplies the source voltage for two diode rectifiers, D_1 and D_2. This transformer has a center-tapped secondary winding that is divided into two equal parts (W1 and W2). W1 provides the source voltage for D_1, and W2 provides the source voltage for D_2. The voltages at the opposite ends of the secondary windings are 180 degrees out of phase with each other. For example, when the voltage at point B is positive with respect to ground, the voltage at point A is negative with respect to ground. The connections to the diodes are arranged so that the diodes conduct on alternate half cycles. Let's examine the operation of the circuit during one complete cycle.

During the first half cycle (indicated by the solid arrows), the voltage at point A is positive with respect to ground, while the voltage at point B is negative with respect to ground. During this alternation, the anode of D_2 is driven negative and D_2 cannot conduct. For the period of time that the anode of D_2 is negative,



Conventional full-wave rectifier

the anode of D_1 is positive, permitting D_1 to conduct. As shown, current flows from point A of the transformer, through diode D_1, down through the load resistor (R_L) to ground (center tap). When D_1 conducts, it acts like a closed switch so that the positive half cycle is felt across the load (R_L).

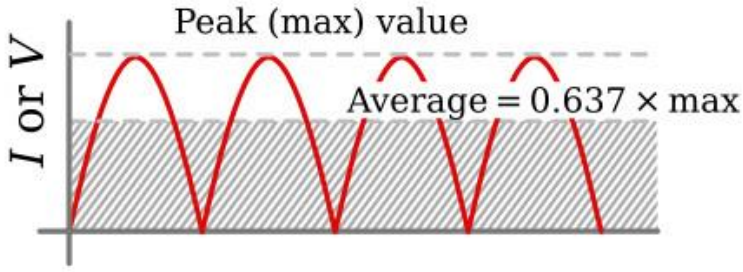
During the second half cycle (indicated by the dashed lines), the polarity of the applied voltage has reversed. Now the anode of D_2 is positive with respect to ground and the anode of D_1 is negative. Now only D_2 can conduct. Current now flows, as shown, from point B of the transformer, through diode D_2, down through the load resistor (R_L) to ground (center tap). Notice that the current

flows across the load resistor (R_L) in the same direction for both halves of the input cycle.

View B of the figure above represents the output waveform from the full-wave rectifier. The waveform consists of two pulses of current (or voltage) for each cycle of input voltage. The ripple frequency at the output of the full-wave rectifier is therefore twice the line frequency.

The higher frequency at the output of a full-wave rectifier offers a distinct advantage: Because of the higher ripple frequency, the output is closely approximate to pure DC. The higher frequency also makes filtering much easier than it is for the output of the half-wave rectifier.

In terms of peak value, the average value of current and voltage at the output of the full-wave rectifier is twice as great as that at the output of the half-wave rectifier. The relationship between the peak value and the average value is illustrated in the figure below. Since the output waveform is essentially a sine wave with both alternations at the same polarity, the average current or voltage is 63.7 percent (or 0.637) of the peak current I_{peak} or voltage V_{peak}.



Peak and average values for a full-wave rectifier.

As an equation:

$$V_{avg} = 0.637 \times V_{peak}$$

$$I_{avg} = 0.637 \times I_{peak}$$

Example:

The total voltage across the high-voltage secondary of a transformer used to supply a full-wave rectifier is 300 volts. Find the average load voltage (ignore the small voltage drop across the diode).

Solution:

Since the total secondary voltage (V_S) is 300 volts, each diode is supplied one-half of this value, or 150 volts. Because the secondary voltage is an RMS value, the peak load voltage is:

$$V_{peak} = 1.414 \times \frac{V_S}{2} = 1.414 \times 150 = 212 \text{ V}$$

The average load voltage is:

$$V_{avg} = 0.637 \times V_{peak} = 0.637 \times 212 = 135 \text{ V}$$

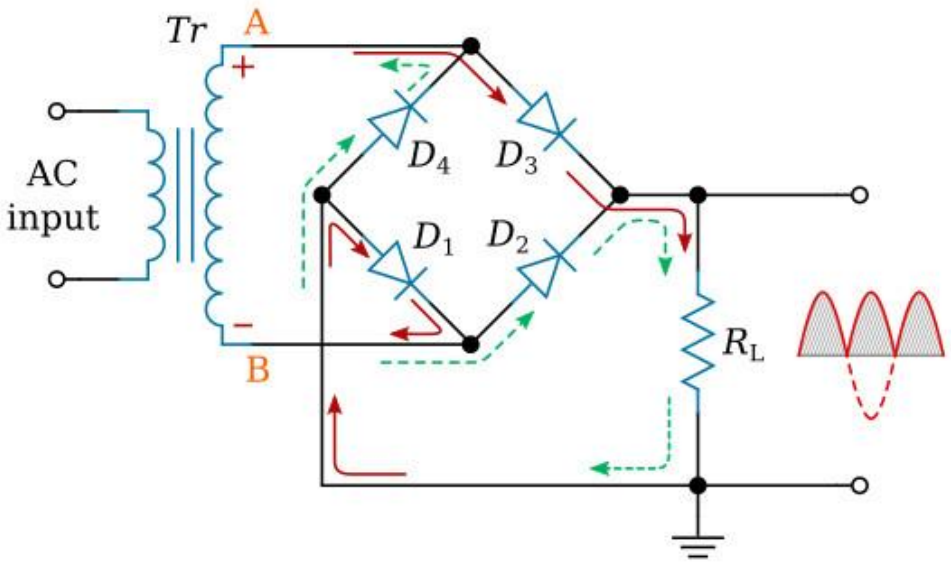
Every electric circuit has advantages and disadvantages. The full-wave rectifier is no exception. In studying the full-wave rectifier, you may have found that by doubling the output frequency, the average voltage has doubled, and the resulting signal is much easier to filter because of the high ripple frequency.

The only disadvantage is that the peak voltage in the full-wave rectifier is only half the peak voltage in the half-wave rectifier. This is because the secondary of the transformer in the full-wave rectifier is center tapped; therefore, only half the source voltage goes to each diode.

Fortunately, there is a rectifier which produces the same peak voltage as a half-wave rectifier and the same ripple frequency as a full-wave rectifier. This circuit, known as the **bridge rectifier**.

The Bridge Rectifier

When four diodes are connected as shown in the figure below, the circuit is called a **bridge rectifier**. The input to the circuit is applied to the diagonally opposite corners of the network, and the output is taken from the remaining two corners.



Bridge rectifier

One complete cycle of operation will be discussed to help you understand how this circuit works. Let us assume that there is a positive potential at point A and a negative potential at point B. The positive potential at point A will forward bias D_3 and reverse bias D_4. The negative potential at point B will forward bias D_1 and reverse bias D_2. At this time D_3 and D_1 are forward biased and will allow current flow to pass through them; D_4 and D_2 are reverse biased and will block current flow. The path for current flow is from point A through D_3, down through R_L, through D_1 to point B. This path is indicated by the solid arrows.

One-half cycle later the polarity across the secondary of the transformer reverses, forward biasing D_2 and D_4 and reverse biasing D_1 and D_3. Current flow will now be from point B through D_2, down through R_L, through D_4 to point A.

This path is indicated by the broken arrows. You should have noted that the current flow through R_L is always in the same direction. In flowing through R_L this current develops a voltage corresponding to that shown in the output waveform. Since current flows through the load (R_L) during both half cycles of the applied voltage, this bridge rectifier is a full-wave rectifier.

One advantage of a bridge rectifier over a conventional full-wave rectifier is that with a given transformer the bridge rectifier produces a voltage output that is nearly twice that of the conventional full-wave circuit.

3.5 Harmonic Components in a Rectifier Circuit

A rectifier circuit is used to convert AC (alternating current) to DC (direct current). When an AC signal is applied to a rectifier circuit, it produces a pulsating DC output signal, which is not a pure DC signal. This pulsating DC signal contains both AC and DC components, and the AC component is known as the harmonic component.

Harmonic components are sinusoidal signals with frequencies that are multiples of the fundamental frequency. In a rectifier circuit, the fundamental frequency is the frequency of the AC input signal. The first harmonic is the fundamental frequency, the second harmonic is twice the fundamental frequency, the third harmonic is three times the fundamental frequency, and so on.

The presence of harmonic components in the output signal of a rectifier circuit is due to the non-linear behavior of the diodes used in the circuit. During the positive half-cycle of the input AC signal, the diode conducts and allows the current to flow through it, while during the negative half-cycle, the diode blocks the current flow. This causes a ripple effect in the output signal, which contains harmonic components.

The harmonic components in the output signal of a rectifier circuit can cause several problems. For example, they can create interference with other electronic devices, generate heat in the circuit components, and cause distortion in audio and video signals.

To reduce the harmonic components in the output signal of a rectifier circuit, several techniques can be used. One common technique is to use a filter circuit, which consists of capacitors and inductors that smooth out the ripple in the output signal. Another technique is to use a transformer to isolate the input and output circuits and reduce the harmonic components in the output signal.

In summary, harmonic components in a rectifier circuit are sinusoidal signals with frequencies that are multiples of the fundamental frequency of the input AC signal. They are caused by the non-linear behavior of the diodes used in the circuit and can cause several problems. To reduce the harmonic components, techniques such as filter circuits and transformers can be used.

3.6 Filter

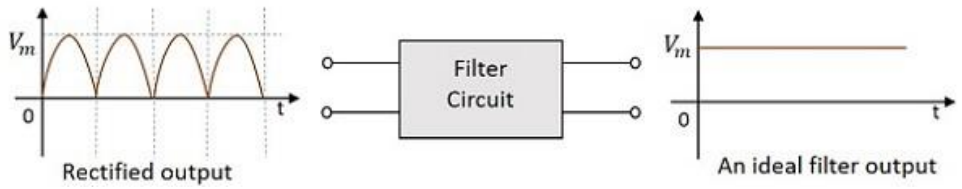
The power supply block diagram clearly explains that a filter circuit is needed after the rectifier circuit. A rectifier helps in converting a pulsating alternating current to direct current, which flows only in one direction. Till now, we have seen different types of rectifier circuits.

The outputs of all these rectifier circuits contain some ripple factor. We have also observed that the ripple factor of a half wave rectifier is greater than that of a full wave rectifier.

The ripple in the signal denotes the presence of some AC component. This ac component has to be completely removed in order to get pure dc output. So, we need a circuit that **smoothens** the rectified output into a pure dc signal.

A **filter circuit** is one which removes the ac component present in the rectified output and allows the dc component to reach the load.

The following figure shows the functionality of a filter circuit.



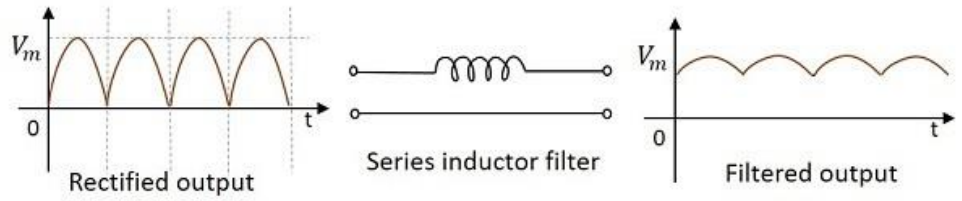
A filter circuit is constructed using two main components, inductor and capacitor. We have already studied in Basic Electronics tutorial that

- An inductor allows **dc** and blocks **ac**.
- A capacitor allows **ac** and blocks **dc**.

Let us try to construct a few filters, using these two components.

Series Inductor Filter

As an inductor allows dc and blocks ac, a filter called **Series Inductor Filter** can be constructed by connecting the inductor in series, between the rectifier and the load. The figure below shows the circuit of a series inductor filter.

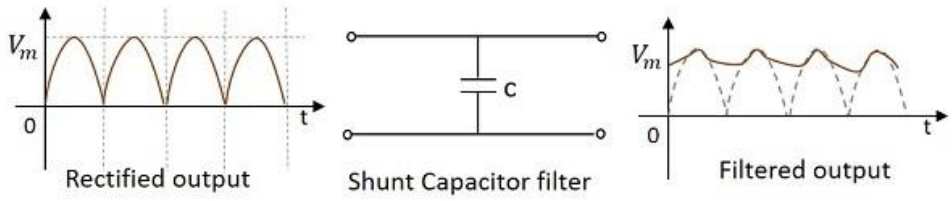


The rectified output when passed through this filter, the inductor blocks the ac components that are present in the signal, in order to provide a pure dc. This is a simple primary filter.

Shunt Capacitor Filter

As a capacitor allows ac through it and blocks dc, a filter called **Shunt Capacitor Filter** can be constructed using a capacitor, connected in shunt, as

shown in the following figure.

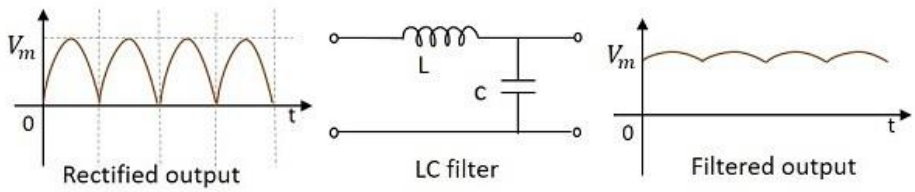


The rectified output when passed through this filter, the ac components present in the signal are grounded through the capacitor which allows ac components. The remaining dc components present in the signal are collected at the output.

The above filter types discussed are constructed using an inductor or a capacitor. Now, let's try to use both of them to make a better filter. These are combinational filters.

L-C Filter

A filter circuit can be constructed using both inductor and capacitor in order to obtain a better output where the efficiencies of both inductor and capacitor can be used. The figure below shows the circuit diagram of a LC filter.



The rectified output when given to this circuit, the inductor allows dc components to pass through it, blocking the ac components in the signal. Now, from that signal, few more ac components if any present are grounded so that we get a pure dc output.

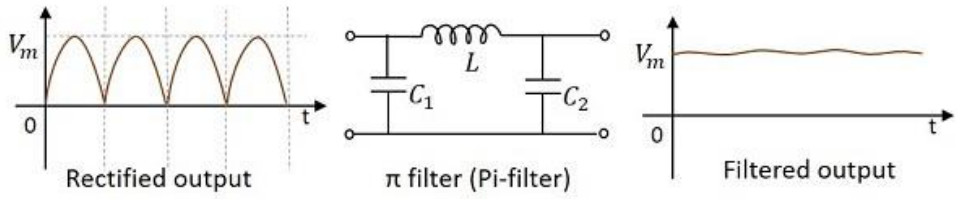
This filter is also called as a **Choke Input Filter** as the input signal first enters the inductor. The output of this filter is a better one than the previous ones.

II- Filter or Pi-filter

This is another type of filter circuit which is very commonly used. It has

capacitor at its input and hence it is also called as a **Capacitor Input Filter**. Here, two capacitors and one inductor are connected in the form of π shaped network. A capacitor in parallel, then an inductor in series, followed by another capacitor in parallel makes this circuit.

If needed, several identical sections can also be added to this, according to the requirement. The figure below shows a circuit for π-filter or Pi−filter.



Working of a Pi filter

In this circuit, we have a capacitor in parallel, then an inductor in series, followed by another capacitor in parallel.

- **Capacitor C_1** − This filter capacitor offers high reactance to dc and low reactance to ac signal. After grounding the ac components present in the signal, the signal passes to the inductor for further filtration.
- **Inductor L** − This inductor offers low reactance to dc components, while blocking the ac components if any got managed to pass, through the capacitor C_1.
- **Capacitor C_2** − Now the signal is further smoothened using this capacitor so that it allows any ac component present in the signal, which the inductor has failed to block.

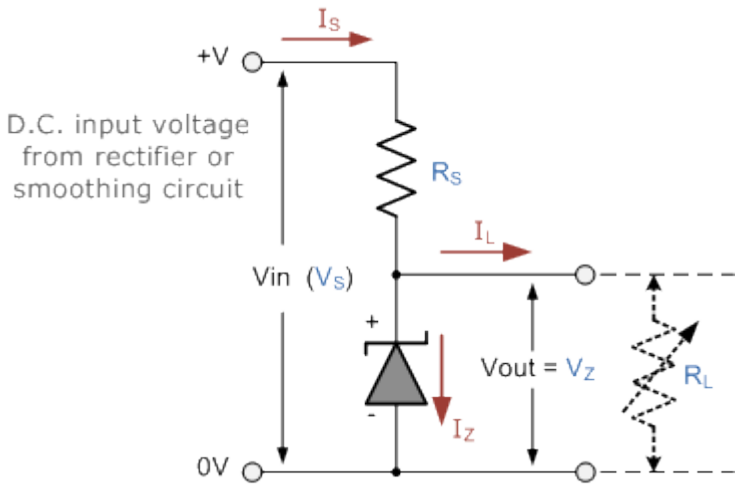
Thus we, get the desired pure dc output at the load.

3.7 Simple Circuit of a Regulator using Zener Diode

Zener Diodes can be used to produce a stabilised voltage output with low ripple under varying load current conditions. By passing a small current through the diode from a voltage source, via a suitable current limiting resistor (R_S), the zener diode will conduct sufficient current to maintain a voltage drop of Vout.

The DC output voltage from the half or full-wave rectifiers contains ripple superimposed onto the DC voltage and that as the load value changes so to does the average output voltage. By connecting a simple zener stabiliser circuit as shown below across the output of the rectifier, a more stable output voltage can be produced.

Zener Diode Regulator



Resistor, R_S is connected in series with the zener diode to limit the current flow through the diode with the voltage source, V_S being connected across the combination. The stabilised output voltage V_{out} is taken from across the zener diode.

The zener diode is connected with its cathode terminal connected to the positive rail of the DC supply so it is reverse biased and will be operating in its breakdown condition. Resistor R_S is selected so to limit the maximum current flowing in the circuit.

With no load connected to the circuit, the load current will be zero, ($I_L = 0$), and all the circuit current passes through the zener diode which in turn dissipates its maximum power.

Also a small value of the series resistor R_S will result in a greater diode current when the load resistance R_L is connected and large as this will increase the power dissipation requirement of the diode so care must be taken when selecting the appropriate value of series resistance so that the zener's maximum power rating is not exceeded under this no-load or high-impedance condition.

The load is connected in parallel with the zener diode, so the voltage across R_L is always the same as the zener voltage, ($V_R = V_Z$).

There is a minimum zener current for which the stabilisation of the voltage is effective and the zener current must stay above this value operating under load within its breakdown region at all times. The upper limit of current is of course dependant upon the power rating of the device. The supply voltage V_S must be greater than V_Z.

One small problem with zener diode stabiliser circuits is that the diode can sometimes generate electrical noise on top of the DC supply as it tries to stabilise the voltage. Normally this is not a problem for most applications but the addition of a large value decoupling capacitor across the zener's output may be required to give additional smoothing.

A zener diode is always operated in its reverse biased condition. As such a simple voltage regulator circuit can be designed using a zener diode to maintain a constant DC output voltage across the load in spite of variations in the input voltage or changes in the load current.

The zener voltage regulator consists of a current limiting resistor R_S connected in series with the input voltage V_S with the zener diode connected in parallel with the load R_L in this reverse biased condition. The stabilised output voltage is always selected to be the same as the breakdown voltage V_Z of the diode.

3.8 Voltage Regulators

A voltage regulator is a device or set of devices designed in such a manner that it maintains the output voltage of a power supply constant to the maximum possible extent. It is also called a closed-loop control system because it provides feedback via examination of output voltages. It compensates for every tendency of output voltages and increases or decreases supply voltage automatically according to requirement. Thus, the objective of a regulator is to eliminate any changes in output voltage (which may result from a load change, input voltage changes, or temperature change). There are two types of voltage regulators.

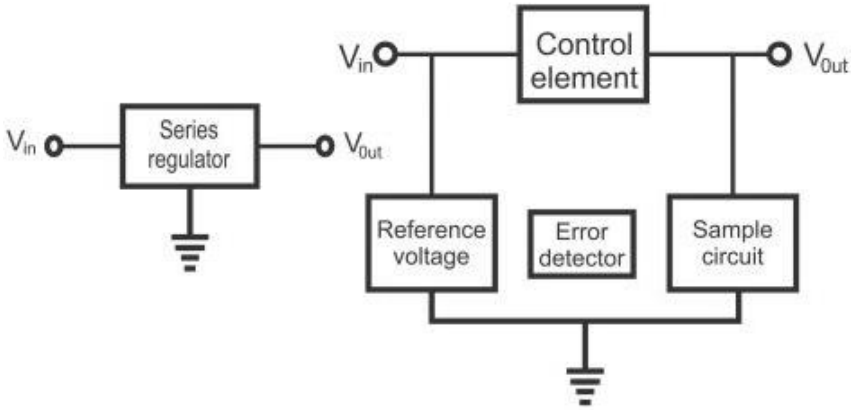
1. Series Voltage Regulator
2. Shunt Voltage Regulator

3.8.1 Series Voltage Regulator

A regulator, the control element (normally a transistor) which is mounted within a series of input voltage and output voltage, is known as a series voltage regulator.

Functional block diagram of a series type regulator has been shown. A functional diagram works as a useful model so that the principles of a series regulator model could easily be understood. Output, senses variations in a simple circuit, output voltage, error detector compares simple voltage with a reference voltage, and thus provides signals to control element for maintaining a constant output voltage. Along with a filter capacitor, unregulated DC input supplied through a rectifier (shown as V_{in} in the diagram), is passed on to the control element mounted in the regulator, through the output of which, regulated output voltages ($\mathbf{V}_0$) are produced. Control Element is a device, by means of which constant output voltages are acquired by adjusting its operating state according to needs. As a control element is being fixed in series between (V_{in}) and (V_0), therefore, such type of regulator is also called series type voltage regulator. A sampling circuit produces feedback proportionate to the output voltage (V_0).

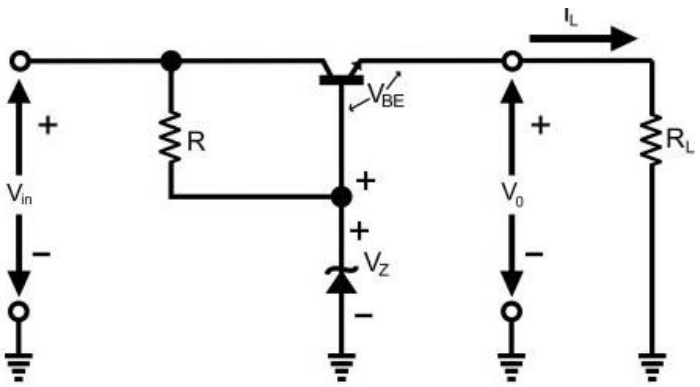
These feedbacks are received by the comparator circuit in the form of a signal, which through mutual comparison of the reference signal and feedback signal provides its output to the control element in the shape of the control signal. This control signal adjusts the operating state of a control element.



Simple series voltage regulator block diagram

Transistor Series Voltage Regulator

A Simple series type voltage regulator consisting of a transistor has been demonstrated. Here, the NPN resistor functions as a control element, which is frequently called a pass transistor, because through conducting, it passes the entire load current through the regulator. Normally, it is a power transistor mounted on a heat sink. Zener diode provides voltage reference. As the entire output voltage (V0) is used for feedback in such types of circuits, therefore, it does not contain any sampling circuit.



A transistor series voltage regulator

As is evident from the diagram, the Zener diode is reverse bias, and reverse current is supplied to it through resistance R. Although, (Vin) is unregulated, its values are kept maximum to a reasonable extent and the value of R kept low to a suitable extent so that Zener could be retained in its reverse breakdown region. Thus, Vz remains constant despite a change in input voltage, (V_z) remains unchanged. If Kirchhoff law is applied around the output loop, we get the following equation

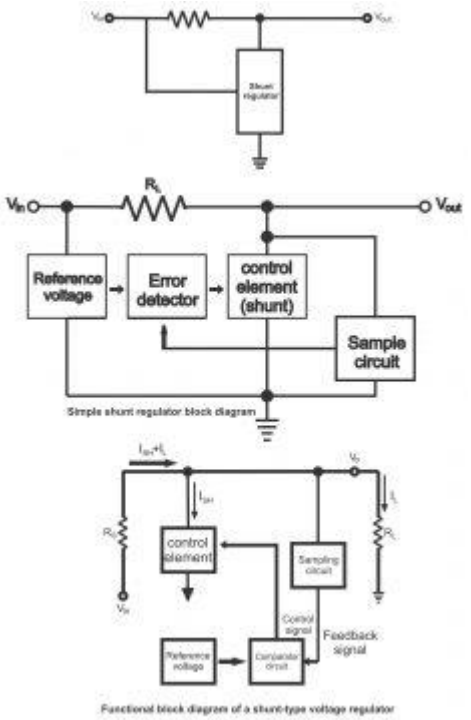
$$V_{BE} = V_z - V_0$$

According to the equation, if (V_z) is constant, a change in (V_{BF}) occurs due to any variation in (V_0). For example, if V_0 is reduced, (V_{BE}) must necessarily increase (as V_z are constant). Similarly, if V_0 increases, (V_{BE}) must decrease.

When V_0 is reduced, (V_{BE}) tends to increase, due to which conduction of NPN transistor also increases. Thus, load current increases, due to which an increase occurs in V0 (because of V_0= IL RL). On contrary, when V_0 increase, (V_{BE}) decreases, due to which transistor's conduction also reduces (i.e. low current passes through it) thus load current, reduces, and resultantly (V_0) also decreases.

3.8.2 Shunt Voltage Regulator

A regulator, the control element of which is parallel to the load, is known as a shunt regulator. For further elucidation, a functional block diagram of a shunt type regulator in figure 6 has been revealed. Components in the block diagram perform exactly the same functions which components in a series regulator use to perform. However, it has to be remembered that the control element in a shunt voltage regulator is parallel to the load, which it is called a shunt regulator. The control element, in case of changes in load current (IL) maintains a constant load voltage on load, by passing a low or high shunt current (I SB) from within it.



If the control element is considered a variable resistance as per the diagram, the process of the control element becomes easy to understand. For example, in case of a decrease in load voltage, the resistance of the control element increases automatically, thus small current flows towards the control element, and load voltages increase. Inversely, if load voltages are increased, the resistance of the control element gets low, thus load voltage decrease due to the passing of more current through the control element.

In other words, source resistance (R_s) on the input or unregulated side of the diagram; assumes the shape of a voltage divider, due to parallel mounting of the control element and (R_L) (i.e. it operates as a voltage divider). Thus, when the resistance of a control element increases, the resistance of the parallel combination increases, and load voltage also increase as a consequence of voltage divider action.

3.9 Study of Clippers

The **Diode Clipper**, also known as a *Diode Limiter*, is a wave shaping circuit that takes an input waveform and clips or cuts off its top half, bottom half or both halves together.

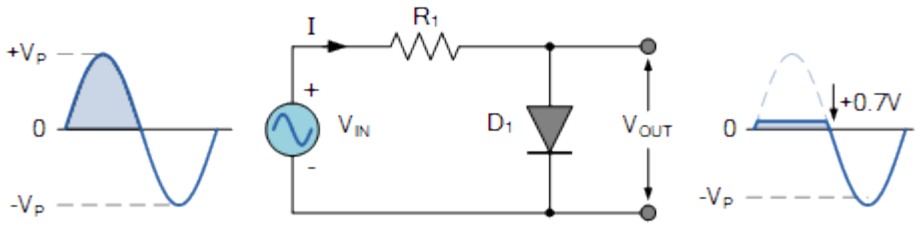
This diode clipping of the input signal produces an output waveform that resembles a flattened version of the input. For example, the half-wave rectifier is a clipper circuit, since all voltages below zero are eliminated.

But **Diode Clipping Circuits** can be used a variety of applications to modify an input waveform using signal and Schottky diodes or to provide over-voltage protection using zener diodes to ensure that the output voltage never exceeds a certain level protecting the circuit from high voltage spikes. Then diode clipping circuits can be used in voltage limiting applications.

We saw in the *Signal Diodes* tutorial that when a diode is forward biased it allows current to pass through itself clamping the voltage. When the diode is reverse biased, no current flows through it and the voltage across its terminals is unaffected, and this is the basic operation of the diode clipping circuit.

Although the input voltage to diode clipping circuits can have any waveform shape, we will assume here that the input voltage is sinusoidal. Consider the circuits below.

Positive Diode Clipping Circuits

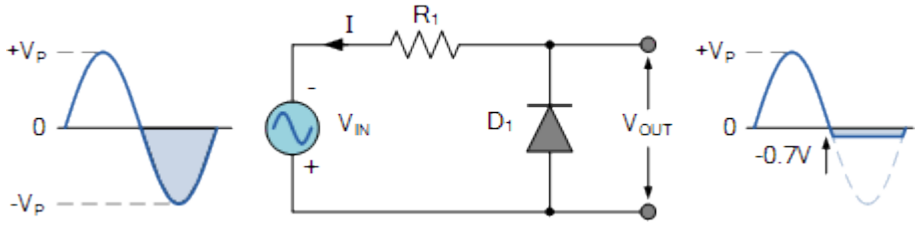


In this diode clipping circuit, the diode is forward biased (anode more positive than cathode) during the positive half cycle of the sinusoidal input waveform. For the diode to become forward biased, it must have the input voltage magnitude greater than +0.7 volts (0.3 volts for a germanium diode).

When this happens the diodes begins to conduct and holds the voltage across itself constant at 0.7V until the sinusoidal waveform falls below this value. Thus the output voltage which is taken across the diode can never exceed 0.7 volts during the positive half cycle.

During the negative half cycle, the diode is reverse biased (cathode more positive than anode) blocking current flow through itself and as a result has no effect on the negative half of the sinusoidal voltage which passes to the load unaltered. Thus the diode limits the positive half of the input waveform and is known as a positive clipper circuit.

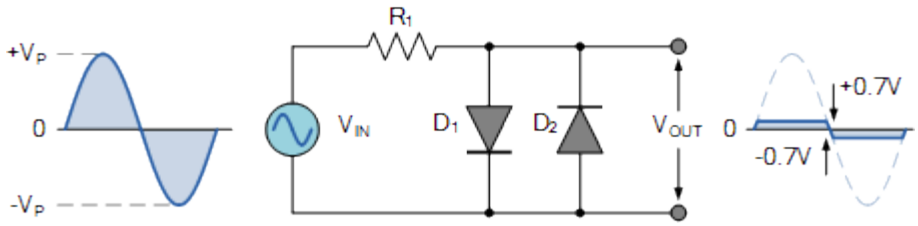
Negative Diode Clipping Circuit



Here the reverse is true. The diode is forward biased during the negative half cycle of the sinusoidal waveform and limits or clips it to –0.7 volts while allowing the positive half cycle to pass unaltered when reverse biased. As the

diode limits the negative half cycle of the input voltage it is therefore called a negative clipper circuit.

Clipping of Both Half Cycles



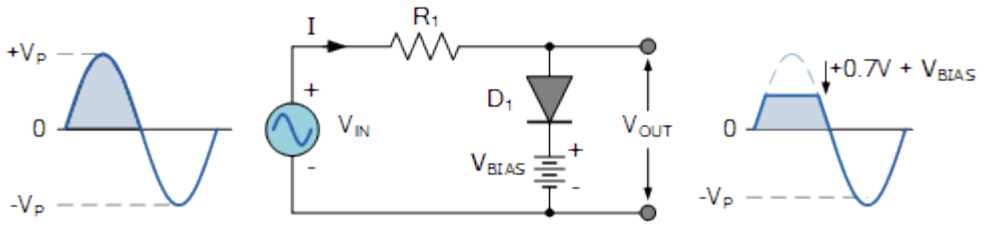
If we connected two diodes in inverse parallel as shown, then both the positive and negative half cycles would be clipped as diode D_1 clips the positive half cycle of the sinusoidal input waveform while diode D_2 clips the negative half cycle. Then diode clipping circuits can be used to clip the positive half cycle, the negative half cycle or both.

For ideal diodes the output waveform above would be zero. However, due to the forward bias voltage drop across the diodes the actual clipping point occurs at +0.7 volts and –0.7 volts respectively. But we can increase this ±0.7V threshold to any value we want up to the maximum value, (V_{PEAK}) of the sinusoidal waveform either by connecting together more diodes in series creating multiples of 0.7 volts, or by adding a voltage bias to the diodes.

Biased Diode Clipping Circuits

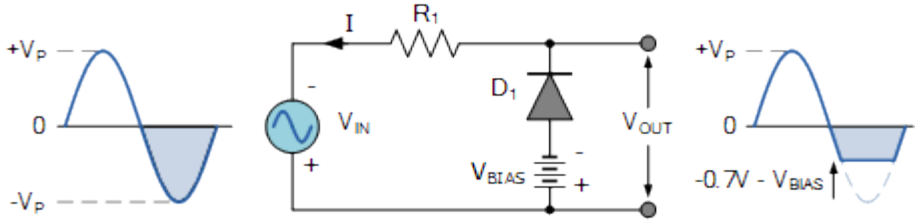
To produce diode clipping circuits for voltage waveforms at different levels, a bias voltage, V_{BIAS} is added in series with the diode to produce a combination clipper as shown. The voltage across the series combination must be greater than V_{BIAS} + 0.7V before the diode becomes sufficiently forward biased to conduct. For example, if the V_{BIAS} level is set at 4.0 volts, then the sinusoidal voltage at the diode's anode terminal must be greater than **4.0 + 0.7 = 4.7 volts** for it to become forward biased. Any anode voltage levels above this bias point are clipped off.

Positive Bias Diode



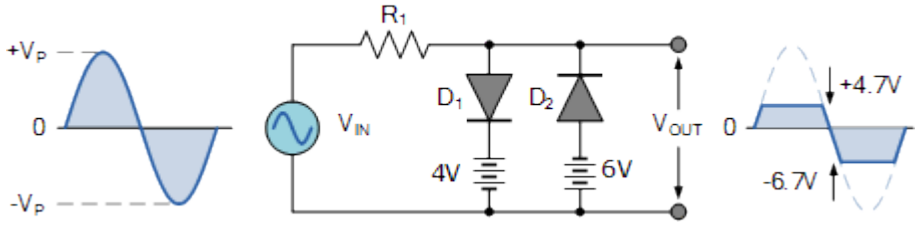
Likewise, by reversing the diode and the battery bias voltage, when a diode conducts the negative half cycle of the output waveform is held to a level – V_{BIAS} – 0.7V as shown.

Negative Bias Diode



A variable diode clipping or diode limiting level can be achieved by varying the bias voltage of the diodes. If both the positive and the negative half cycles are to be clipped, then two biased clipping diodes are used. But for both positive and negative diode clipping, the bias voltage need not be the same. The positive bias voltage could be at one level, for example 4 volts, and the negative bias voltage at another, for example 6 volts as shown.

Diode Clipping of Different Bias levels



When the voltage of the positive half cycle reaches +4.7 V, diode D_1 conducts and limits the waveform at +4.7 V. Diode D_2 does not conduct until the voltage reaches –6.7 V. Therefore, all positive voltages above +4.7 V and negative

voltages below –6.7 V are automatically clipped.

The advantage of biased diode clipping circuits is that it prevents the output signal from exceeding preset voltage limits for both half cycles of the input waveform, which could be an input from a noisy sensor or the positive and negative supply rails of a power supply.

If the diode clipping levels are set too low or the input waveform is too great then the elimination of both waveform peaks could end up with a square-wave shaped waveform.

Zener Diode Clipping Circuits

The use of a bias voltage means that the amount of the voltage waveform that is clipped off can be accurately controlled. But one of the main disadvantages of using voltage biased diode clipping circuits, is that they need an additional emf battery source which may or may not be a problem.

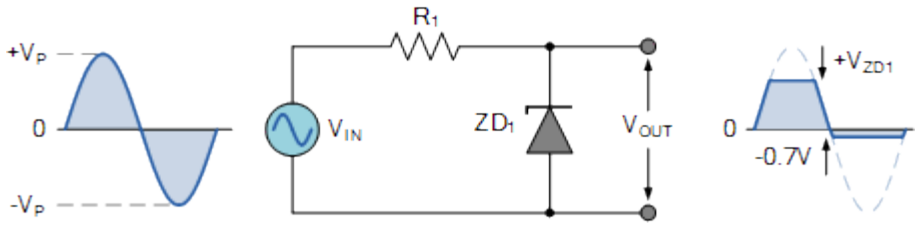
One easy way of creating biased diode clipping circuits without the need for an additional emf supply is **to use Zener Diodes.**

As we know, the zener diode is a another type of diode that has been specially manufactured to operate in its reverse biased breakdown region and as such can be used for voltage regulation or zener diode clipping applications. In the forward region, the zener acts just like an ordinary silicon diode with a forward voltage drop of 0.7V (700mV) when conducting, the same as above.

However, in the reverse bias region, the voltage is blocked until the zener diodes breakdown voltage is reached. At this point, the reverse current through the zener increases sharply but the zener voltage, V_Z across the device remains constant even if the zener current, I_Z varies.

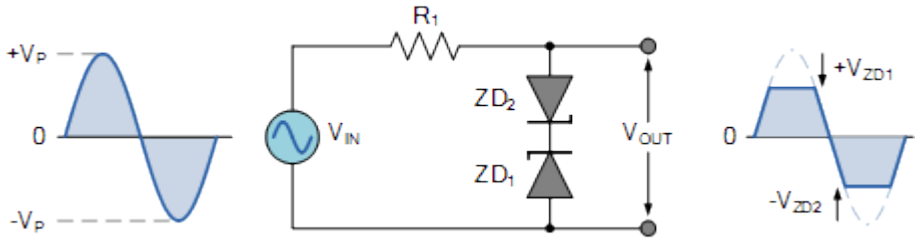
Then we can put this zener action to good effect by using them for clipping a waveform as shown.

Zener Diode Clipping



The zener diode is acting like a biased diode clipping circuit with the bias voltage being equal to the zener breakdown voltage. In this circuit during the positive half of the waveform the zener diode is reverse biased so the waveform is clipped at the zener voltage, V_{ZD1}. During the negative half cycle the zener acts like a normal diode with its usual 0.7V junction value.

Full-wave Zener Diode Clipping



The output waveform from full wave zener diode clipping circuits resembles that of the previous voltage biased diode clipping circuit. The output waveform will be clipped at the zener voltage plus the 0.7V forward volt drop of the other diode. So for example, the positive half cycle will be clipped at the sum of zener diode, ZD_1 plus 0.7V from ZD_2 and vice versa for the negative half cycle.

Zener diodes are manufactured with a wide range of voltages and can be used to give different voltage references on each half cycle, the same as above. Zener diodes are available with zener breakdown voltages, V_Z ranging from 2.4 to 33 volts, with a typical tolerance of 1 or 5%. Note that once conducting in the

reverse breakdown region, full current will flow through the zener diode so a suitable current limiting resistor, R_1 must be chosen.

Diode Clipping Circuits are used to eliminate amplitude noise or voltage spikes, voltage regulation or to produce new waveforms from an existing signal such as squaring off the peaks of a sinusoidal waveform to obtain a rectangular waveform

3.10 Clampers

A Clamper Circuit is a circuit that adds a DC level to an AC signal. Actually, the positive and negative peaks of the signals can be placed at desired levels using the clamping circuits. As the DC level gets shifted, a clamper circuit is called as a **Level Shifter**.

Clamper circuits consist of energy storage elements like capacitors. A simple clamper circuit comprises of a capacitor, a diode, a resistor and a dc battery if required.

Clamper Circuit

A Clamper circuit can be defined as the circuit that consists of a diode, a resistor and a capacitor that shifts the waveform to a desired DC level without changing the actual appearance of the applied signal.

In order to maintain the time period of the wave form, the **tau** must be greater than, half the time period discharging time of the capacitor should be slow.

$$\tau=Rc$$

Where

- R is the resistance of the resistor employed
- C is the capacitance of the capacitor used

The time constant of charge and discharge of the capacitor determines the output of a clamper circuit.

- In a clamper circuit, a vertical shift of upward or downward takes place in the output waveform with respect to the input signal.
- The load resistor and the capacitor affect the waveform. So, the discharging time of the capacitor should be large enough.

The DC component present in the input is rejected when a capacitor coupled network is used as a capacitor blocks dc. Hence when **dc** needs to be **restored**, clamping circuit is used.

Types of Clampers

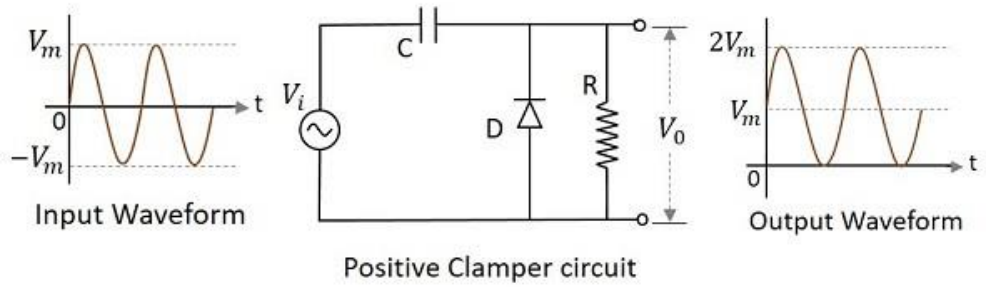
There are few types of clamper circuits, such as

- Positive Clamper
- Positive clamper with positive Vr
- Positive clamper with negative Vr
- Negative Clamper
- Negative clamper with positive Vr
- Negative clamper with negative Vr

Positive Clamper Circuit

A Clamping circuit restores the DC level. When a negative peak of the signal is raised above to the zero level, then the signal is said to be **positively clamped**.

A Positive Clamper circuit is one that consists of a diode, a resistor and a capacitor and that shifts the output signal to the positive portion of the input signal. The figure below explains the construction of a positive clamper circuit.



Initially when the input is given, the capacitor is not yet charged and the diode is reverse biased. The output is not considered at this point of time. During the negative half cycle, at the peak value, the capacitor gets charged with negative on one plate and positive on the other. The capacitor is now charged to its peak value Vm. The diode is forward biased and conducts heavily.

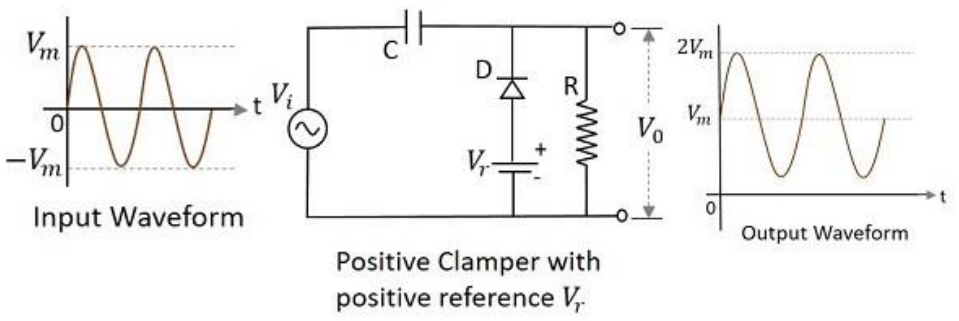
During the next positive half cycle, the capacitor is charged to positive Vm while the diode gets reverse biased and gets open circuited. The output of the circuit at this moment will be

$$V_0=V_i+V_m$$

Hence the signal is positively clamped as shown in the above figure. The output signal changes according to the changes in the input, but shifts the level according to the charge on the capacitor, as it adds the input voltage.

Positive Clamper with Positive V_r

A Positive clamper circuit if biased with some positive reference voltage, that voltage will be added to the output to raise the clamped level. Using this, the circuit of the positive clamper with positive reference voltage is constructed as below.

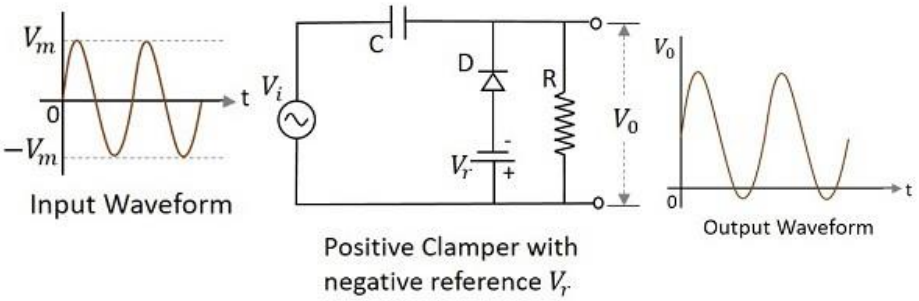


Positive Clamper with positive reference V_r

During the positive half cycle, the reference voltage is applied through the diode at the output and as the input voltage increases, the cathode voltage of the diode increase with respect to the anode voltage and hence it stops conducting. During the negative half cycle, the diode gets forward biased and starts conducting. The voltage across the capacitor and the reference voltage together maintain the output voltage level.

Positive Clamper with Negative Vr

A Positive clamper circuit if biased with some negative reference voltage, that voltage will be added to the output to raise the clamped level. Using this, the circuit of the positive clamper with positive reference voltage is constructed as below.

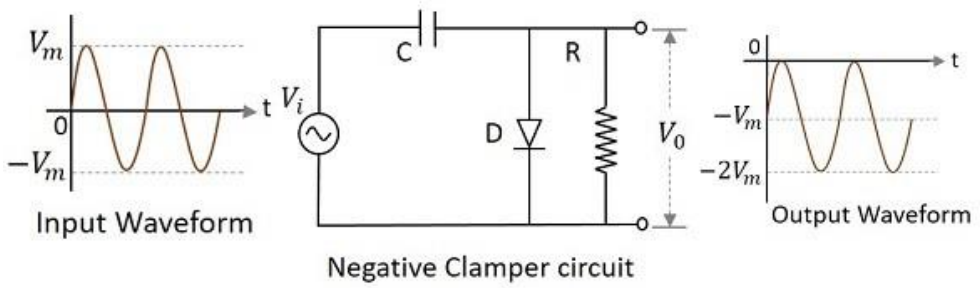


Positive Clamper with negative reference V_r

During the positive half cycle, the voltage across the capacitor and the reference voltage together maintain the output voltage level. During the negative half-cycle, the diode conducts when the cathode voltage gets less than the anode voltage. These changes make the output voltage as shown in the above figure.

Negative Clamper

A Negative Clamper circuit is one that consists of a diode, a resistor and a capacitor and that shifts the output signal to the negative portion of the input signal. The figure below explains the construction of a negative clamper circuit.



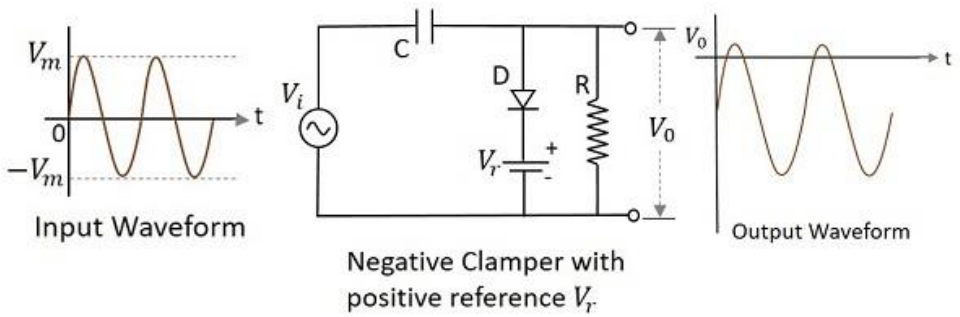
During the positive half cycle, the capacitor gets charged to its peak value v_m. The diode is forward biased and conducts. During the negative half cycle, the diode gets reverse biased and gets open circuited. The output of the circuit at this moment will be

$$V_0=V_i+V_m$$

Hence the signal is negatively clamped as shown in the above figure. The output signal changes according to the changes in the input, but shifts the level according to the charge on the capacitor, as it adds the input voltage.

Negative clamper with positive V_r

A Negative clamper circuit if biased with some positive reference voltage, that voltage will be added to the output to raise the clamped level. Using this, the circuit of the negative clamper with positive reference voltage is constructed as below.

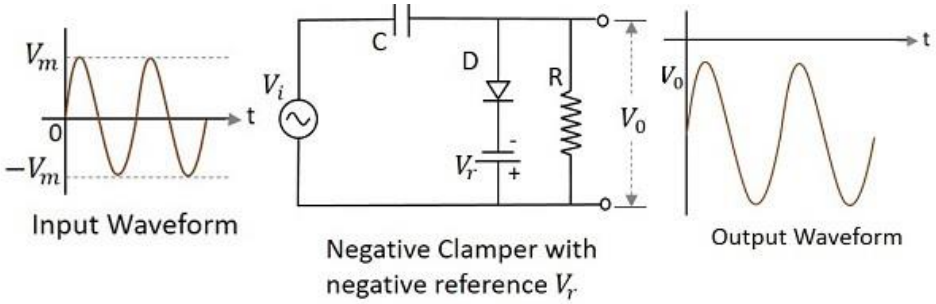


Though the output voltage is negatively clamped, a portion of the output

waveform is raised to the positive level, as the applied reference voltage is positive. During the positive half-cycle, the diode conducts, but the output equals the positive reference voltage applied. During the negative half cycle, the diode acts as open circuited and the voltage across the capacitor forms the output.

Negative Clamper with Negative V_r

A Negative clamper circuit if biased with some negative reference voltage, that voltage will be added to the output to raise the clamped level. Using this, the circuit of the negative clamper with negative reference voltage is constructed as below.



The cathode of the diode is connected with a negative reference voltage, which is less than that of zero and the anode voltage. Hence the diode starts conducting during positive half cycle, before the zero voltage level. During the negative half cycle, the voltage across the capacitor appears at the output. Thus the waveform is clamped towards the negative portion.

Applications of Clampers

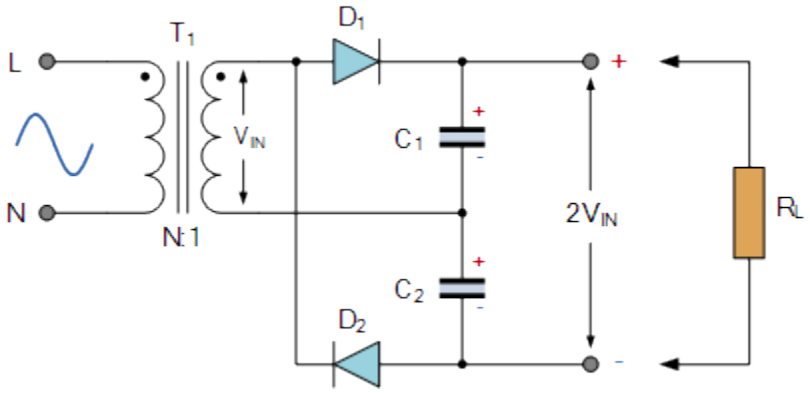
- Used as direct current restorers
- Used to remove distortions
- Used as voltage multipliers
- Used for the protection of amplifiers
- Used as test equipment
- Used as base-line stabilizer

3.11 Voltage Multipliers

An electronic circuit consisting of diodes and capacitors and converts an AC electrical signal from a lower voltage value to a higher DC voltage value is referred to as a **voltage multiplier**. Voltage multipliers are used in several electronic appliances to generate a voltage signal of few volts to millions of volts.

A **Voltage Multiplier** is an electronic circuit consisting of capacitors and diodes and is used to multiply or rise the voltage level of an AC signal. The voltage multiplier receives an AC voltage of lower value, converts it into a DC voltage and increases its voltage level. Therefore, a voltage multiplier circuit performs both rectification and multiplication of voltage. Here, the rectification operation is performed by diodes and the increase in voltage is achieved by the capacitors.

Full Wave Voltage Multiplier



The above circuit shows a basic symmetrical voltage multiplier circuit made up from two half-wave rectifier circuits. By adding a second diode and capacitor to the output of a standard half-wave rectifier, we can increase its output voltage by a set amount. This type of voltage multiplier configuration is known as a **Full Wave Series Multiplier** because one of the diodes is conducting in each half cycle, the same as for a full wave rectifier circuit.

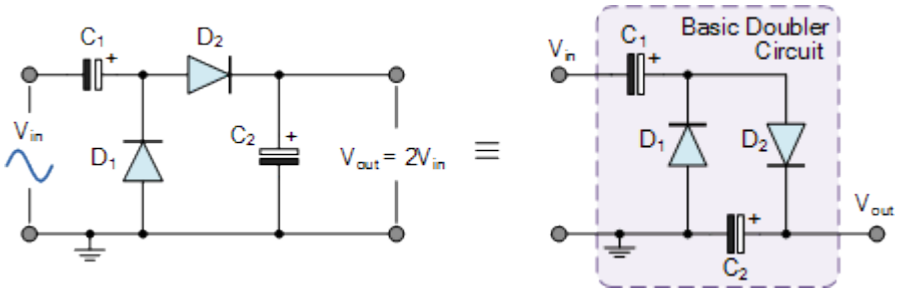
When the sinusoidal input voltage is positive, capacitor C_1 charges up through diode D_1 and when the sinusoidal voltage is negative, capacitor C_2 charges up through diode, D_2. The output voltage $2V_{IN}$ is taken across the two series connected capacitors.

The voltage produced by a *voltage multiplier* circuit is in theory unlimited, but due to their relatively poor voltage regulation and low current capability there are generally designed to increase the voltage by a factor less than ten. However, if designed correctly around a suitable transformer, voltage multiplier circuits are capable of producing output voltages in the range of a few hundred to tens's of thousand's of volts, depending upon their original input voltage value but all with low currents in the milliamperes range.

The Voltage Doubler

As its name suggests, a **Voltage Doubler** is a voltage multiplier circuit which has a voltage multiplication factor of two. The circuit consists of only two diodes, two capacitors and an oscillating AC input voltage (a PWM waveform could also be used). This simple diode-capacitor pump circuit gives a DC output voltage equal to the peak-to-peak value of the sinusoidal input. In other words, double the peak voltage value because the diodes and the capacitors work together to effectively double the voltage.

DC Voltage Doubler Circuit



The circuit shows a half wave voltage doubler. During the negative half cycle of

the sinusoidal input waveform, diode D1 is forward biased and conducts charging up the pump capacitor, C1 to the peak value of the input voltage, (Vp). Because there is no return path for capacitor C1 to discharge into, it remains fully charged acting as a storage device in series with the voltage supply. At the same time, diode D2 conducts via D1 charging up capacitor, C2.

During the positive half cycle, diode D1 is reverse biased blocking the discharging of C1 while diode D2 is forward biased charging up capacitor C2. But because there is a voltage across capacitor C1 already equal to the peak input voltage, capacitor C2 charges to twice the peak voltage value of the input signal.

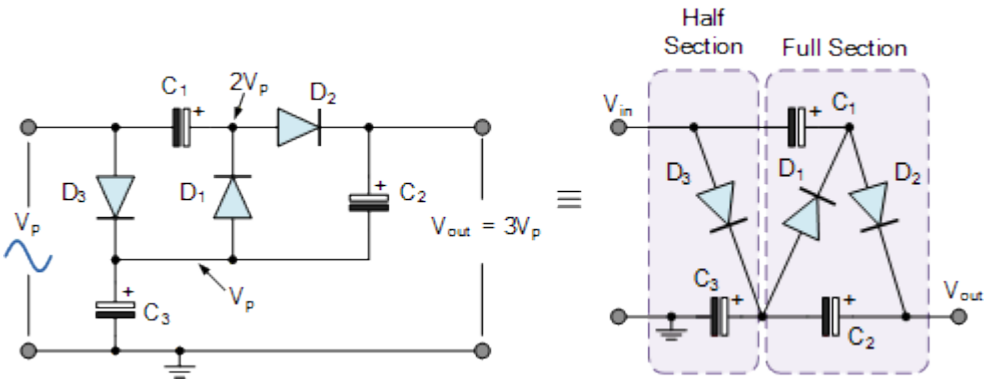
In other words, V(positive peak) + V(negative peak), so on the negative half-cycle, D1 charges C1 to Vp and on the positive half-cycle D2 adds the AC peak voltage to Vp onC1 and transfers it all to C2. The voltage across capacitor, C2 discharges through the load ready for the next half cycle.

Then the voltage across capacitor, C2 can be calculated as: Vout = 2Vp, (minus of course the voltage drops across the diodes used) where Vp is the peak value of the input voltage. Note that this double output voltage is not instantaneous but increases slowly on each input cycle, eventually settling to 2Vp.

As capacitor C2 only charges up during one half cycle of the input waveform, the resulting output voltage discharged into the load has a ripple frequency equal to the supply frequency, hence the name half wave voltage doubler. The disadvantage of this is that it can be difficult to smooth out this large ripple frequency in much the same way as for a half wave rectifier circuit. Also, capacitor C2 must have a DC voltage rating at least twice the value of the peak input voltage.

The advantage of "Voltage Multiplier Circuits" is that it allows higher voltages to be created from a low voltage power source without a need for an expensive high voltage transformer as the voltage doubler circuit makes it possible to use a transformer with a lower step up ratio than would be need if an ordinary full wave supply were used. However, while voltage multipliers can boost the voltage, they can only supply low currents to a high-resistance (+100kΩ) load because the generated output voltage quickly drops-off as load current increases. By reversing the direction of the diodes and capacitors in the circuit we can also reverse the direction of the output voltage creating a negative voltage output. Also, if we connected the output of one multiplying circuit onto the input of another (cascading), we can continue to increase the DC output voltage in integer steps to produce voltage triplers, or voltage quadruplers circuits, etc, as shown.

DC Voltage Tripler Circuit



By adding an additional single diode-capacitor stage to the half-wave voltage doubler circuit above, we can create another voltage multiplier circuit that increases its input voltage by a factor of three and producing what is called a **Voltage Tripler Circuit**.

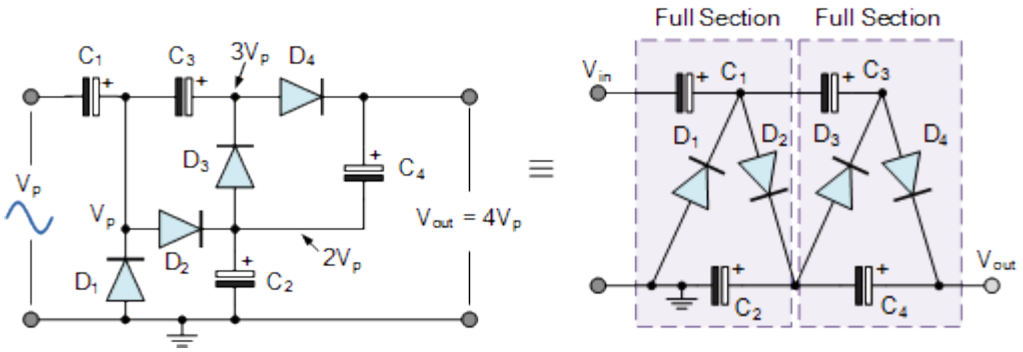
A "voltage tripler circuit" consists of one and a half voltage doubler stages. This voltage multiplier circuit gives a DC output equal to three times the peak voltage

value (3Vp) of the sinusoidal input signal. As with the previous voltage doubler, the diodes within the voltage tripler circuit charge and block the discharge of the capacitors depending upon the direction of the input half-cycle. Then 1Vp is dropped across C3 and 2Vp across C2 and as the two capacitors are in series, this results in the load seeing a voltage equivalent to 3Vp.

Note that the real output voltage will be three times the peak input voltage minus the voltage drops across the diodes used, 3Vp – V(diode).

If a voltage tripler circuit can be made by cascading together one and a half voltage multipliers, then a **Voltage Quadrupler Circuit** can be constructed by cascading together two full voltage doubler circuits as shown.

DC Voltage Quadrupler Circuit



The first voltage multiplier stage doubles the peak input voltage and the second stage doubles it again, giving a DC output equal to four times the peak voltage value (4Vp) of the sinusoidal input signal. Also, using large value capacitors will help to reduce the ripple voltage.

Chapter 4
Amplifiers and Oscillators

Small Signal Low Frequency Transistor Amplifier Circuits – h-Parameter Representation of a Transistor – Analysis of Single Stage Transistor Amplifier using h-Parameter – Voltage Gain – Current Gain – Input Impedance and Output Impedance – Comparison of Transistor Configurations – Condition for Sustained Oscillation – Types of Oscillators

4.1 Introduction

Amplifiers and oscillators are two essential components in the field of electronics. Amplifiers are devices that amplify the strength of an electrical signal, while oscillators are devices that generate electrical signals with a specific frequency. In this introduction, we will discuss amplifiers and oscillators in detail.

Amplifiers: An amplifier is a device that increases the power or amplitude of an electrical signal. Amplifiers are used to amplify signals in a wide range of applications, including audio systems, radio communication, and instrumentation. There are different types of amplifiers, including voltage amplifiers, current amplifiers, and power amplifiers.

Voltage amplifiers are designed to increase the voltage level of a signal. They are often used in audio amplifiers, where they amplify the low-level audio signals from a microphone or a turntable to a level that can drive speakers.

Current amplifiers are used to increase the current level of a signal. They are commonly used in radio frequency (RF) amplifiers, where they amplify the low-level signals from an antenna to a level that can be demodulated by a receiver.
Power amplifiers are used to increase the power level of a signal. They are commonly used in audio systems, where they amplify the signal from a preamplifier to a level that can drive speakers.

Oscillators: An oscillator is a device that generates an electrical signal with a specific frequency. Oscillators are used in a wide range of applications, including radio communication, electronic test equipment, and digital systems. There are different types of oscillators, including sine wave oscillators, square wave oscillators, and pulse wave oscillators.

Sine wave oscillators generate a pure sine wave with a specific frequency. They are commonly used in RF and audio applications, where a stable sine wave is required.

Square wave oscillators generate a square wave with a specific frequency. They are commonly used in digital systems, where the square wave is used as a clock signal.

Pulse wave oscillators generate a pulse wave with a specific frequency. They are commonly used in digital systems, where the pulse wave is used as a trigger signal.

In conclusion, amplifiers and oscillators are essential components in the field of electronics. Amplifiers are used to increase the strength of an electrical signal, while oscillators are used to generate electrical signals with a specific frequency. Different types of amplifiers and oscillators are used in a wide range of applications, including audio systems, radio communication, and digital systems.

4.2 Small Signal Low Frequency Transistor Amplifier Circuits

V-I characteristics of an active device such as BJT are non-linear. The analysis of a non- linear device is complex. Thus to simplify the analysis of the BJT, its operation is restricted to the linear V-I characteristics around the Q-point i.e. in the active region. This approximation is possible only with small input signals. With small input signals transistor can be replaced with small signal linear model. This model is also called small signal equivalent circuit.

Two –Port Devices and Network Parameters

All the transistor amplifiers are two port networks having two voltages and two currents. The positive directions of voltages and currents are shown in **fig. 1**.

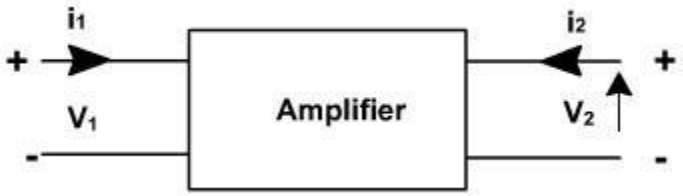


Fig. 1

A two-port network is represented by four external variables: voltage V1 and current I1 at the input port, and voltage V2 and current I2 at the output port, so that the two-port network can be treated as a black box modeled by the relationships between the four variables,V1,V2, I1,I2 . Out of four variables two can be selected as are independent variables and two are dependent variables. The dependent variables can be expressed interns of independent variables. This leads to various two port parameters out of which the following three are important:

1. Impedance parameters (z-parameters)
2. Admittance parameters (y-parameters)
3. Hybrid parameters (h-parameters)

Hybrid parameters (h-parameters)

If the input current I1 and output voltage V2 are taken as independent variables, the dependent variables V1 and I2 can be written as

$$\begin{bmatrix} V_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ V_2 \end{bmatrix}$$

Where h11, h12, h21, h22 are called as hybrid parameters.

$$h_{11} = \left. \frac{V_1}{I_1} \right|_{V_2=0}$$

Input impedence with o/p port short circuited

$$h_{12} = \left. \frac{V_1}{V_2} \right|_{I_1=0}$$

Reverse voltage transfer ratio with i/p port open circuited

$$h_{21} = \left. \frac{I_2}{I_1} \right|_{V_2=0}$$

Forward voltage transfer ratio with o/p port short circuited

$$h_{22} = \left. \frac{I_2}{V_2} \right|_{I_1=0}$$

output impedance with i/p port open circuited

The Hybrid Model For Two Port Network:

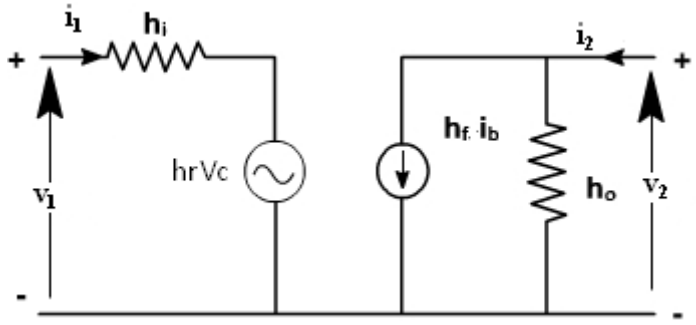
Based on the definition of hybrid parameters the mathematical model for two pert networks known as h-parameter model can be developed. The hybrid equations can be written as:

$$V_1 = h_i I_1 + h_r V_2$$

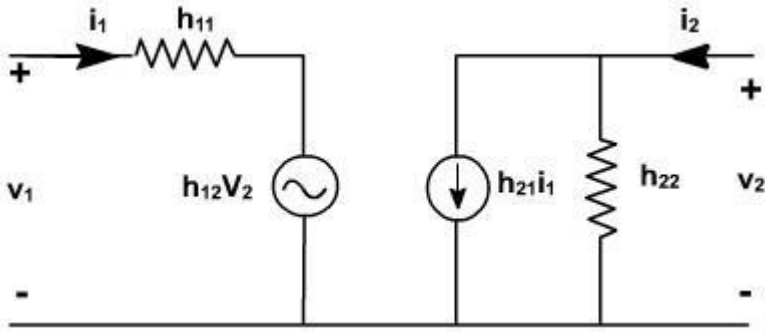
$$I_2 = h_f I_1 + h_o V_2$$

***i*=11= input *o* = 22 = output *f* =21 = forward transfer *r* = 12 = reverse transfer**

We may now use the four h parameters to construct a mathematical model of the device of Fig.(1). The hybrid circuit for any device indicated in Fig.(2). We can verify that the model of Fig.(2) satisfies above equations by writing Kirchhoff's voltage and current laws for input and output ports.



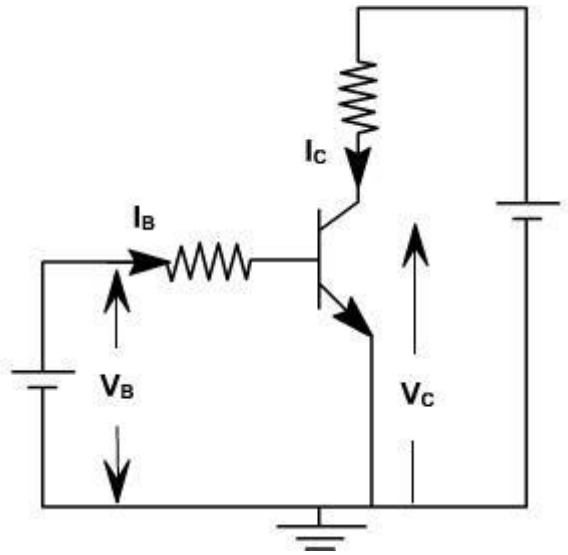
If these parameters are specified for a particular configuration, then suffixes e,b or c are also included, e.g. hfe ,hib are h parameters of common emitter and common collector amplifiers. Using two equations the generalized model of the amplifier can be drawn as shown in fig.



4.3 h-Parameter Representation of a Transistor

The hybrid model for a transistor amplifier can be derived as follow:

Let us consider CE configuration as show in fig. 3. The variables, iB, iC ,vC, and vB represent total instantaneous currents and voltages iB and vC can be taken as independent variables and vB, IC as dependent variables.



VB = f1 (iB ,vC) IC = f2 (iB ,vC).

Using Taylor 's series expression, and neglecting higher order terms we obtain.

$$\Delta v_B = \left.\frac{\partial f_1}{\partial i_B}\right|_{v_C} \Delta i_B + \left.\frac{\partial f_1}{\partial v_C}\right|_{i_B} \Delta v_C$$

$$\Delta i_C = \left.\frac{\partial f_2}{\partial i_B}\right|_{v_C} \Delta i_B + \left.\frac{\partial f_2}{\partial v_C}\right|_{i_B} \Delta v_C$$

The partial derivatives are taken keeping the collector voltage or base current constant. The Δ vB, Δ vC, Δ iB, Δ iC represent the small signal (incremental) base and collector current and voltage and can be represented as vB, iC, iB ,vC

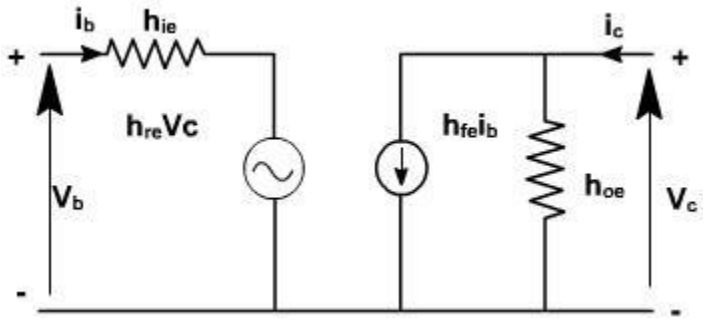
$$\therefore v_b = h_{ie}\, i_B + h_{re}\, v_C$$
$$i_C = h_{fe}\, i_B + h_{oe}\, v_b$$

where

$$h_{ie} = \left.\frac{\partial f_1}{\partial i_B}\right|_{v_C} = \left.\frac{\partial v_B}{\partial i_B}\right|_{v_C}; \qquad h_{re} = \left.\frac{\partial f_1}{\partial v_C}\right|_{i_B} = \left.\frac{\partial v_B}{\partial v_C}\right|_{i_B}$$

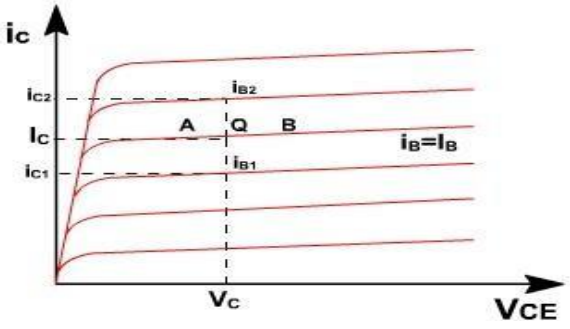
$$h_{fe} = \left.\frac{\partial f_2}{\partial i_B}\right|_{v_C} = \left.\frac{\partial i_C}{\partial i_B}\right|_{v_C}; \qquad h_{oe} = \left.\frac{\partial f_2}{\partial v_C}\right|_{i_B} = \left.\frac{\partial v_B}{\partial v_C}\right|_{i_B}$$

The model for CE configuration is shown in fig.



To determine the four h-parameters of transistor amplifier, input and output characteristic are used. Input characteristic depicts the relationship between input voltage and input current with output voltage as parameter. The output characteristic depicts the relationship between output voltage and output current with input current as parameter, shows the output characteristics of CE amplifier.

$$h_{fe} = \left.\frac{\partial i_C}{\partial i_B}\right|_{V_C} = \frac{i_{C2} - i_{C1}}{i_{b2} - i_{b1}}$$



The current increments are taken around the quiescent point Q which corresponds to iB = IB and to the collector voltage VCE = VC

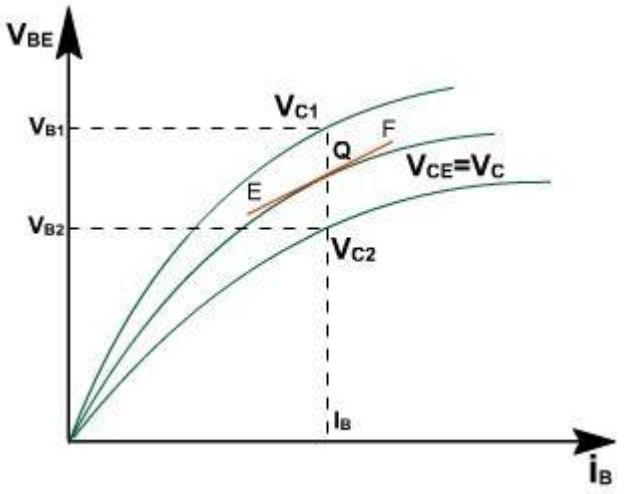
$$h_{oe} = \left.\frac{\partial i_C}{\partial V_C}\right|_{i_B}$$

The value of hoe at the quiescent operating point is given by the slope of the output characteristic at the operating point (i.e. slope of tangent AB).

$$h_{ie} = \frac{\partial V_B}{\partial i_B} \approx \left.\frac{\Delta V_B}{\Delta i_B}\right|_{V_C}$$

hie is the slope of the appropriate input on **fig.**, at the operating point (slope of tangent EF at Q).

$$h_{re} = \frac{\partial V_B}{\partial V_C} = \left.\frac{\Delta V_B}{\Delta V_C}\right|_{I_B} = \frac{V_{B2} - V_{B1}}{V_{C2} - V_{C1}}$$



A vertical line on the input characteristic represents constant base current. The parameter hre can be obtained from the ratio (VB2– V B1) and (VC2– V C1) for at Q.

Typical CE h-parametersof transistor 2N1573 are given below: hie = 1000 ohm.

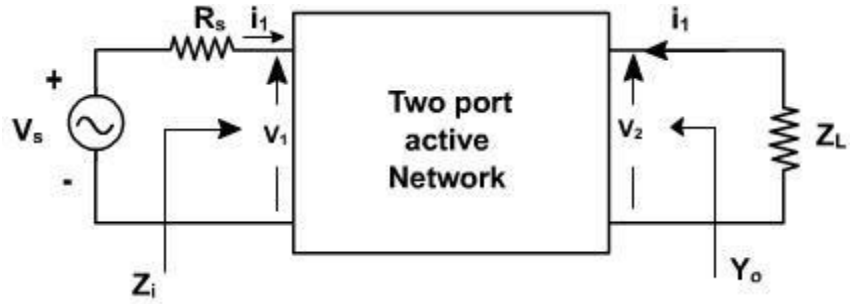
hre = $2.5 * 10^{-4}$

hfe = 50

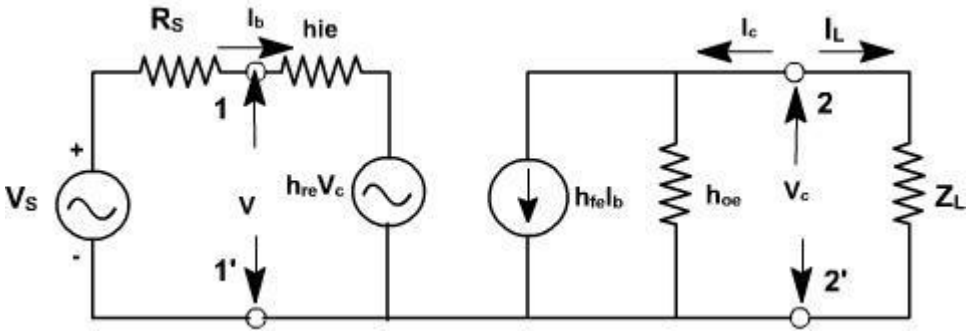
hoe = 25 μ A / V

4.4 Analysis of Single Stage Transistor Amplifier using h-Parameter

To form a transistor amplifier it is only necessary to connect an external load and signal source as indicated in **fig** and to bias the transistor properly.



Consider the two-port network of CE amplifier. RS is the source resistance and ZL is the load impedance h-parameters are assumed to be constant over the operating range. The ac equivalent circuit is shown in **fig.**(Phasor notations are used assuming sinusoidal voltage input). The quantities of interest are the current gain, input impedence, voltage gain, and output impedence.



4.5 Voltage gain:

The ratio of output voltage to input voltage gives the gain of the transistors.

$$A_v = \frac{V_C}{V_b} = -\frac{I_C Z_L}{V_b}$$

$$\therefore A_v = \frac{I_B A_i Z_L}{V_b} = \frac{A_i Z_L}{Z_i}$$

4.6 Current gain:

For the transistor amplifier stage, Ai is defined as the ratio of output to input currents.

$$A_I = \frac{I_L}{I_1} = \frac{-I_2}{I_1}$$

4.7 Input Impedance and Output Impedance

Input impedance:

The impedance looking into the amplifier input terminals (1,1') is the input impedence Zi.

$$Z_i = \frac{V_b}{I_b}$$

$$V_b = h_{ie} I_b + h_{re} V_c$$

$$\frac{V_b}{I_b} = h_{ie} + h_{re} \frac{V_c}{I_b}$$

$$= h_{ie} - \frac{h_{re} I_c Z_L}{I_b}$$

$$\therefore Z_i = h_{ie} + h_{re} A_I Z_L$$

$$= h_{ie} - \frac{h_{re} h_{fe} Z_L}{1 + h_{oe} Z_L}$$

$$\therefore Z_i = h_{ie} - \frac{h_{re} h_{fe}}{Y_L + h_{oe}} \qquad (\text{since } Y_L = \frac{1}{Z_L})$$

Output Admittance:

It is defined as

$$Y_0 = \left.\frac{I_c}{V_c}\right|_{V_s = 0}$$

$$I_c = h_{fe} I_b + h_{oe} V_c$$

$$\frac{I_c}{V_c} = h_{fe} \frac{I_b}{V_c} + h_{oe}$$

when $V_s = 0$, $\quad R_s . I_b + h_{ie} . I_b + h_{re} V_c = 0.$

$$\frac{I_b}{V_c} = -\frac{h_{re}}{R_s + h_{ie}}$$

$$\therefore Y_0 = h_{oe} - \frac{h_{re} h_{fe}}{R_s + h_{ie}}$$

Voltage amplification taking into account source impedance (R_S) is given by

$$A_{VS} = \frac{V_c}{V_s} = \frac{V_c}{V_b} * \frac{V_b}{V_S} \qquad \left(V_b = \frac{V_s}{R_s + Z_i} * Z_i\right)$$

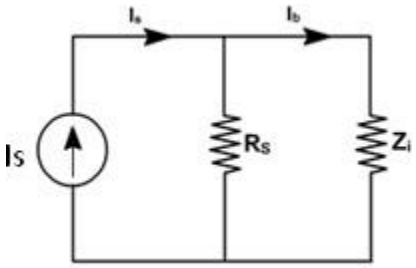
$$= A_V . \frac{Z_i}{Z_i + R_s}$$

$$= \frac{A_i Z_L}{Z_i + R_s}$$

Av is the voltage gain for an ideal voltage source (Rv = 0).

Consider input source to be a current source IS in parallel with a resistance RS

as shown in **fig.**



In this case, overall current gain AIS is defined as

$$A_{I_s} = \frac{I_L}{I_s}$$

$$= -\frac{I_c}{I_s}$$

$$= -\frac{I_c}{I_b} * \frac{I_b}{I_s} \qquad \left(I_b = \frac{I_s * R_s}{R_s + Z_i} \right)$$

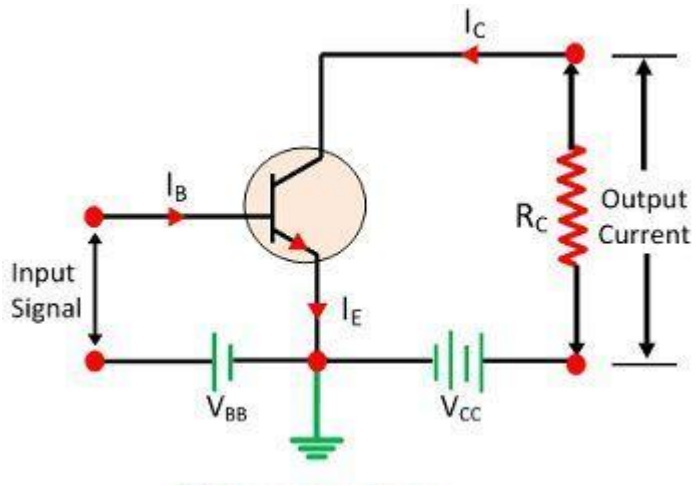
$$= A_I * \frac{R_s}{R_s + Z_i}$$

$$\text{If } R_s \to \infty, \quad A_{I_s} \to A_I$$

Transistor Hybrid Model

The basic assumption in arriving at a transistor linear model or equivalent circuit is that the variations about the operating or quiescent point are small and, therefore, the transistor parameters can be considered constant over the small range of operation.

Many transistor models have been proposed, each one having its particular merits and demerits. The transistor model presented here, is given in terms of the h parameters, which are real numbers at audio frequencies, are easy to measure, can also be obtained from the static characteristics of a transistor, and are particularly convenient to use in analysis and design of circuit. Furthermore, a set of h parameters is specified for many transistors by the manufacturers.



To derive a hybrid model for a transistor, let us consider the basic CE amplifier circuit given in Fig. 11.7. The variables i_B, i_C, v_B and v_C represent the total instantaneous values of currents and voltages. We may select the input current i_B and output voltage v_C as independent variables. Since input voltage v_B is some function f_1 of i_B and v_C and output current i_C is another function f_2 of i_B and v_C, we may write

$$v_B = f_1(i_B, v_C)$$
$$i_C = f_2(i_B, v_C)$$

Making a Taylor's series expansion of Eqs. And about the zero signal operating point (I_B, V_C) and neglecting higher-order terms we have

$$\Delta v_B = \left.\frac{\delta f_1}{\delta i_B}\right|_{V_C} \Delta i_B + \left.\frac{\delta f_1}{\delta v_C}\right|_{I_B} \Delta v_C$$

$$\Delta i_C = \left.\frac{\delta f_2}{\delta i_B}\right|_{V_C} \Delta i_B + \left.\frac{\delta f_2}{\delta v_C}\right|_{I_B} \Delta v_C$$

where partial derivatives $\delta f_1/\delta i_B$ and $\delta f_2/\delta i_B$ are taken, keeping collector voltage V_C constant while partial derivates $\delta f_1/\delta v_C$ and $\delta f_2/\delta v_C$ are taken, keeping base current I_B constant.

The quantities Δv_B, Δv_C, Δi_B and Δi_C represent the small-signal (incremental) base and collector voltages and currents and may be represented as v_b, v_c, i_b, and i_c respectively as per standard notations. We may now write Eqs. as below

$$v_b = h_{ie} i_b + h_{re} v_c$$
$$i_c = h_{fe} i_b + h_{oe} v_c$$

$$\text{where } h_{ie} \equiv \left.\frac{\delta f_1}{\delta i_B}\right|_{V_C} = \left.\frac{\delta v_B}{\delta i_B}\right|_{V_C} = \left.\frac{v_b}{i_b}\right|_{V_C = 0}$$

$$h_{fe} \equiv \left.\frac{\delta f_2}{\delta i_B}\right|_{V_C} = \left.\frac{\delta i_C}{\delta i_B}\right|_{V_C} = \left.\frac{i_c}{i_b}\right|_{V_C = 0}$$

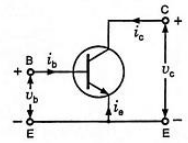
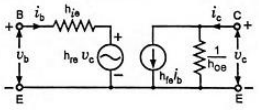
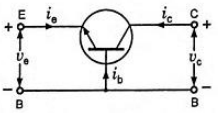
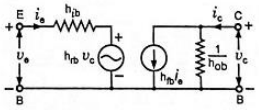
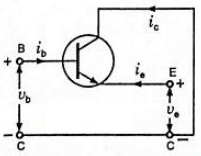
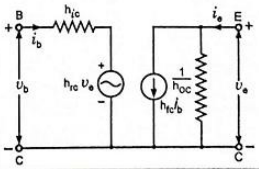
$$h_{re} \equiv \left.\frac{\delta f_1}{\delta v_C}\right|_{I_B} = \left.\frac{\delta v_B}{\delta v_C}\right|_{I_B} = \left.\frac{v_b}{v_c}\right|_{I_B = 0}$$

$$h_{oe} \equiv \left.\frac{\delta f_2}{\delta v_C}\right|_{I_B} = \left.\frac{\delta i_C}{\delta v_C}\right|_{I_B} = \left.\frac{i_c}{v_c}\right|_{I_B = 0}$$

The partial derivatives of Eq. (11.9) define the h parameters for the transistor in common-emitter (CE) configuration.

4.8 Comparison of Transistor Configurations

The common-emitter (CE), common-base (CB), and common-collector (CC) configurations, their Transistor Hybrid Model and their terminal volt-ampere equations are summarized in Table

Configuration	*Circuit Schematic*	*Hybrid Model*	*v-i Equations*
Common Emitter, CE			$v_b = h_{ie} i_b + h_{re} v_c$ $i_c = h_{fe} i_b + h_{oe} v_c$
Common Base, CB			$v_e = h_{ib} i_e + h_{rb} v_c$ $i_c = h_{fb} i_e + h_{ob} v_c$
Common Collector CC			$v_b = h_{ic} i_b + h_{rc} v_e$ $i_e = h_{fc} i_b + h_{oc} v_e$

The circuits and equations in Table are valid for either an N-P-N or P-N-P transistor and are independent of the type of load or biasing method.

4.9 Condition for Sustained Oscillation

Sustained oscillation is the continuous and repetitive motion of a system around a fixed equilibrium point. In order for a system to exhibit sustained oscillation, it must meet certain conditions, which vary depending on the type of system. Here are some common conditions for sustained oscillation:

1. **Feedback:** The system must have a feedback loop, meaning that some part of the output of the system is fed back into the input. This can create a self-reinforcing cycle that leads to sustained oscillation.

2. **Nonlinearity:** Nonlinear systems are more likely to exhibit sustained oscillation than linear systems. This is because nonlinear systems can have more complex and varied behavior, which can lead to oscillations.

3. **Delay:** Systems with a delay in the feedback loop can also exhibit sustained oscillation. This delay can create a phase shift between the input and output, which can lead to oscillations.

4. **Instability:** In some cases, sustained oscillation can arise from an unstable equilibrium point. If the system is pushed slightly away from the equilibrium point, it will continue to oscillate around it rather than returning to it.

5. **Resonance:** Resonance can also lead to sustained oscillation. If the system is subjected to a periodic input that matches the system's natural frequency, it can start oscillating at that frequency and continue to do so.

6. **Energy:** In mechanical systems, sustained oscillation can occur if the system has enough energy to overcome damping forces. In this case, the system will continue to oscillate until it loses enough energy to come to a stop.

Overall, the conditions for sustained oscillation depend on the specific system and its properties. Understanding these conditions can help predict and control oscillations in various systems, from electronic circuits to biological rhythms.

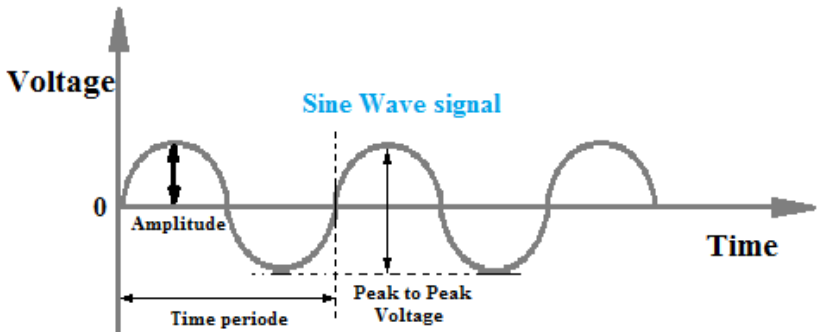
4.10 Types of Oscillators

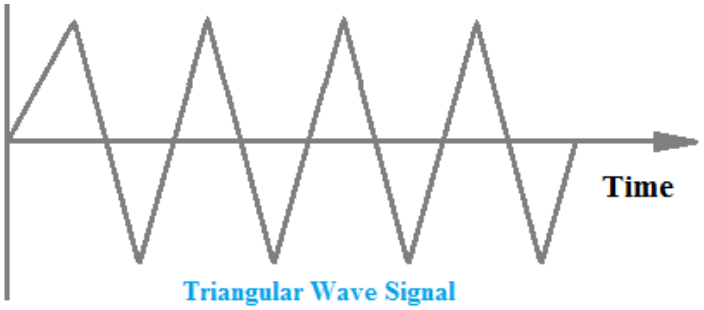
An **Oscillator is an electronic circuit or device which** can convert a steady state signal into an oscillating signal. For example, the oscillator can convert a steady state DC signal into a periodic AC signal of the desired frequency.

There is a huge **application of Oscillator** in electronics engineering and also it is widely used in electrical engineering. Actually, the oscillation not only related to electrical or electronics, but there is mechanical **oscillator** also available.

Definition of Oscillator: The oscillator is a device (may be electrical or maybe mechanical) which can create oscillation of steady state energy (may be electrical energy or mechanical energy).

As we represent the electrical energy by the electrical or electronic signal and waveforms theoretically that is why we used the word Signal instead of energy in the definition of an **electronic oscillator**.





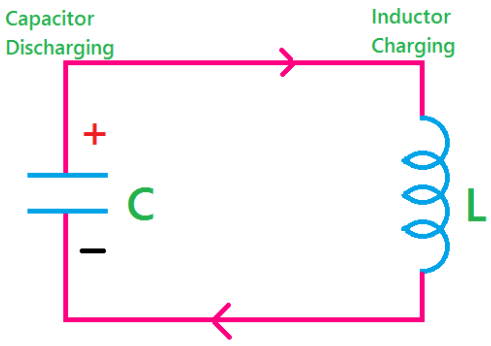
Triangular Wave Signal

Oscillating Signal

The signals of different frequency for different different applications like in digital electronics most of the devices like Flip-Flop circuits, Registers etc need a clock pulse for their operation. The clock pulse or clock signal is nothing but an oscillating signal. Even the CPU of the computer needs a clock pulse. As the oscillating signals have a frequency that is why they are used for many applications.

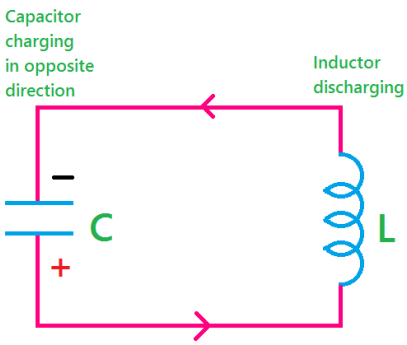
Simple oscillator circuit:

The basic concepts of an **oscillator** can be given by a simple electrical circuit which consists of a capacitor and an inductor connected in parallel. But remember that you must have the basic knowledge of Inductor and Capacitor to understand that circuit. We know that the capacitor store the electrical energy in the form of charge and the inductor can also store electrical energy but in the form of electromagnetic magnetic field.



As you see in the above figures a capacitor and an inductor are connected in parallel. Assume the capacitor is fully precharged, so now the capacitor starts discharging through the inductor and the electrical energy is storing into the inductor in form of the electromagnetic field. When the capacitor is fully discharged there will be no current flow in the circuit. In this condition, the capacitor is fully discharged and the inductor is fully charged.

Now the inductor starts discharging through the capacitor and the capacitor start charging in the opposite polarity. So this charging and discharging of the capacitor and inductor makes the oscillating signal or we can say the repeatable get and paid of electrical energy between the capacitor and inductor creates the oscillations.



The inter-conversion of energy cannot continue forever because of energy losses. The energy loss will occur due to the resistance of the circuit. For this reason, the oscillation becomes decreasing and a time will come when the oscillation will be zero.

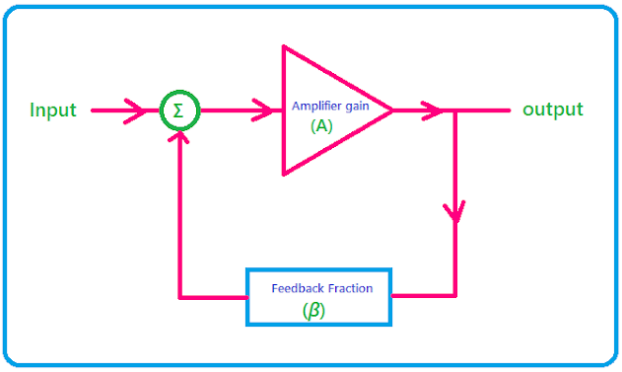
So a simple oscillator circuit can be made by capacitor and inductor but it cannot give the continuous oscillation and of constant amplitude.

Oscillator circuit using Amplifier:

The oscillator circuit can be made by an amplifier with feedback. The feedback

may be positive or regenerative. The feedback means a part of the output signal of the amplifier is fed back to the input of the amplifier. The oscillator circuit using an amplifier can give continuous constant amplitude oscillations.

So when we applied some sinusoidal signal as the input of the amplifier the output of the amplifier will be the multiplication of the gain of the amplifier and the input signal. Now the output of the amplifier is given to the feedback circuit as the input. Generally, the feedback circuit is nothing but a frequency selective circuit or resonant circuit and it decides what fraction of the output signal of the amplifier is to be given to the input of the amplifier as feedback signals.



When the output signal of the feedback circuit is added to the input signal and at the same time the input signal of the amplifier is removed the feedback signal will act as the input of the amplifier. Now after removing the input signal, we can decide which type of oscillation (sustain or not) we want to get and this depends upon the multiplication of the gain of the amplifier and the feedback fraction of the feedback circuit.

So from the above explanation, it is cleared that the input of the oscillator circuit does not need all over the time during the operation of the oscillator. The input is needed only for starting the oscillation and once the oscillation is started the input can be removed or in other words, the oscillator can give the output

without input.

Types of Oscillator:

Oscillator circuit has a feedback path so according to the feedback path,

1. Positive Feedback Oscillator
2. Negative Feedback Oscillator

Oscillator circuit creates an oscillating signal which may be many types in Waveform. So based on the types of waveform the Oscillator classified as below,

1. Sine Wave Oscillator
2. Rectangular or square wave Oscillator
3. Sawtooth Wave oscillator

Based on the circuit design,

1. LC Oscillator
2. RC Oscillator
3. Crystal Oscillator

According to the frequency range,

1. Low-Frequency Oscillator
2. High-Frequency Oscillator
3. Very High-Frequency Oscillator
4. Ultra High-Frequency Oscillator

Examples of Oscillator:

Some examples of oscillators are Royer Oscillator, Tri-tet Oscillator, Armstrong Oscillator, Meissner Oscillator, Pierce Oscillator, Ring Oscillator etc.

Applications of Oscillator:

There are huge applications of oscillators which are given below,

1. The oscillator is used in Watches.
2. Oscillators are used in Radio Circuits.
3. Oscillators are used smart phones, computer laptops etc.
4. Royer Oscillators are used in some DC to AC Inverter circuits.
5. Armstrong Oscillator is used to very high-frequency sinusoidal signals.
6. Pierce Oscillators are mainly used in crystal oscillator circuits.
7. Oscillators are used in stun guns.
8. Oscillators are used in ultrasonic machines.
9. In metal detector oscillators are also used.

Chapter 5
Digital System

Number System – Binary, Decimal, Octal, Hexadecimal – Binary Addition Subtraction, Multiplication & Division– Boolean Algebra – Reduction of Boolean Expressions – Logic Gates - De-Morgan's Theorem - Adder – Subtractor

5.1 Introduction

A digital system is a system that processes information using digital signals, which are represented by binary digits (bits) that can take the values 0 or 1. Digital systems are used in a wide range of applications, including computers, smartphones, digital cameras, and many other electronic devices.

The basic building blocks of a digital system are logic gates, which are electronic circuits that perform simple Boolean operations such as AND, OR, and NOT. These gates can be combined to create more complex circuits, such as adders, counters, and multiplexers, which are used to perform arithmetic and logical operations.

Digital systems can also include memory elements, such as registers and flip-flops, which store data and enable the system to retain information over time. In addition, digital systems typically include input and output devices, such as keyboards, displays, and sensors, which allow the system to interact with the outside world.

One of the key advantages of digital systems is their ability to store and process information accurately and reliably. This is due to the fact that digital signals are less susceptible to noise and distortion than analog signals, which are continuous in nature. As a result, digital systems can be used to perform a wide range of tasks with a high degree of precision and accuracy.

Overall, digital systems have revolutionized the way we communicate, compute, and interact with the world around us, and their importance is only likely to grow in the years to come.

5.2 Number System

A number system is a way of representing numbers using symbols or digits. There are several number systems that are commonly used in mathematics and computer science, including the decimal, binary, octal, and hexadecimal number systems.

Number systems can be converted from one system to another using conversion formulas or by using digital calculators or computer programs. The ability to convert between number systems is important in computer science, as computers use binary numbers to represent all data and instructions.

5.3 Binary, Decimal, Octal, Hexadecimal Number System

The four most commonly used number systems in computer science and digital electronics are binary, decimal, octal, and hexadecimal. Here's a brief overview of each:

1. **Binary Number System:** The binary number system is the most basic number system in computing, as it only uses two digits, 0 and 1. Each digit in a binary number is called a bit. In digital electronics, binary is used to represent logic states, where 0 represents a low voltage and 1 represents a

high voltage. Binary numbers are also used to represent data and instructions in computer programs.

2. **Decimal Number System:** The decimal number system is the number system most commonly used in everyday life. It uses ten digits (0 to 9) to represent all numbers. Each digit in a decimal number has a place value based on powers of 10. For example, in the number 123, the digit 1 represents 100, the digit 2 represents 10, and the digit 3 represents 1.

3. **Octal Number System:** The octal number system uses eight digits (0 to 7) to represent all numbers. Each digit in an octal number has a place value based on powers of 8. Octal numbers are commonly used in digital electronics and computer programming, as they are a convenient way of representing binary numbers. Each group of three bits in a binary number can be converted to a single octal digit.

4. **Hexadecimal Number System:** The hexadecimal number system uses sixteen digits (0 to 9 and A to F) to represent all numbers. Each digit in a hexadecimal number has a place value based on powers of 16. Hexadecimal numbers are commonly used in digital electronics and computer programming, as they are a convenient way of representing binary numbers. Each group of four bits in a binary number can be converted to a single hexadecimal digit.

In computer programming and digital electronics, it is common to use a prefix to indicate which number system is being used. For example, the prefix "0b" is often used to indicate a binary number, "0d" for a decimal number, "0o" for an octal number, and "0x" for a hexadecimal number.

Decimal	Binary	Octal	Hexadecimal
0	0	0	0
1	1	1	1
2	10	2	2
3	11	3	3
4	100	4	4
5	101	5	5
6	110	6	6
7	111	7	7
8	1000	10	8
9	1001	11	9
10	1010	12	A
11	1011	13	B
12	1100	14	C
13	1101	15	D
14	1110	16	E
15	1111	17	F
16	10000	20	10

5.4 Number System Conversion

Decimal to Binary, Octal and Hexadecimal Conversions

a) Decimal to Binary Conversion

Decimal = 41

Division	Quotient	Remainder
41/2	20	1
20/2	10	0
10/2	5	0
5/2	2	1
2/2	1	0
1/2	0	1

Binary = 101001

b) Decimal to Octal Conversion

Decimal = 415

Division	Quotient	Remainder
415/8	51	7
51/8	6	3
6/8	0	6

Octal = 637

c) Decimal to Hexadecimal Conversion

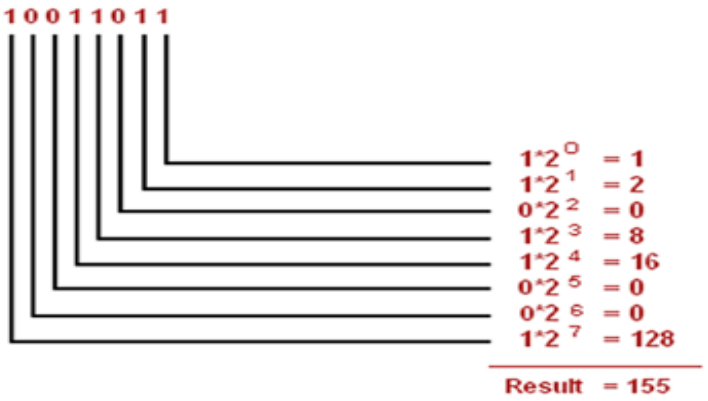
Decimal = 4156

Division	Quotient	Remainder
4156/16	259	12 – C
259/16	16	3
16/16	1	0
1/16	0	1

Hexadecimal = 103C

Binary to Decimal, Octal and Hexadecimal Conversions

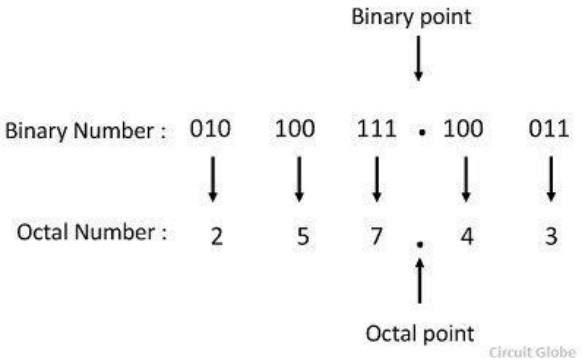
a) Binary to Decimal Conversion



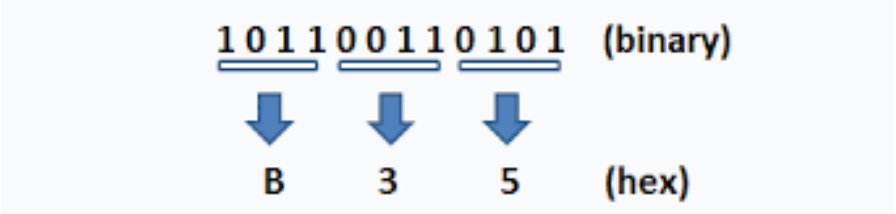
Binary = 10011011

Decimal = 155

b) Binary to Octal Conversion

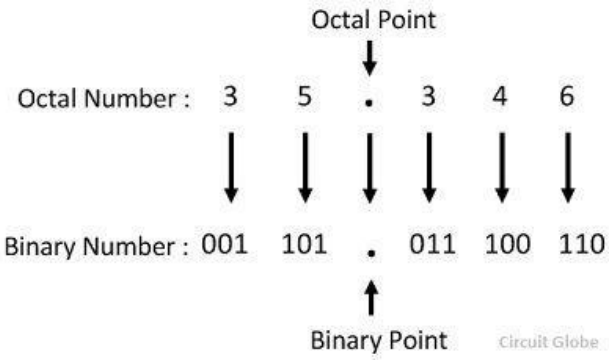


c) Binary to Hexadecimal Conversion

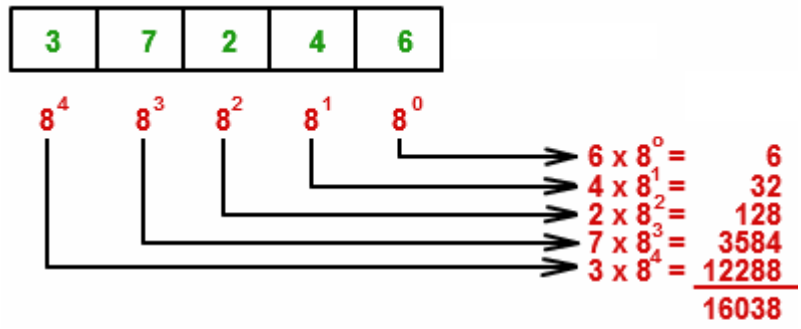


Octal to Binary, Decimal and Hexadecimal Conversions

a) Octal to Binary Conversion



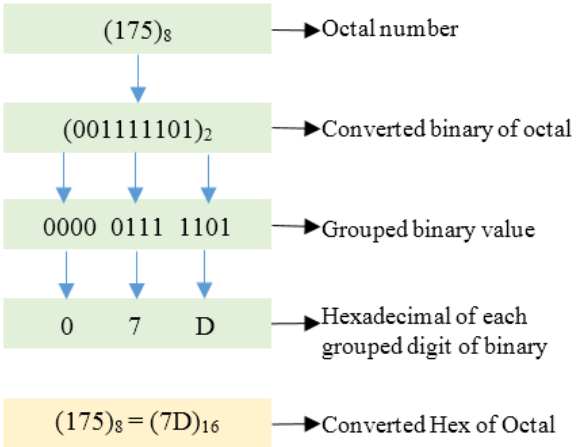
b) Octal to Decimal Conversion



Octal = 37246

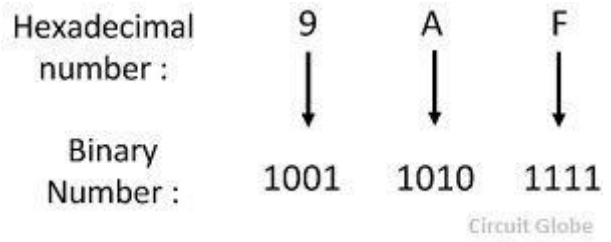
Decimal = 16038

c) Octal to Hexadecimal Conversion

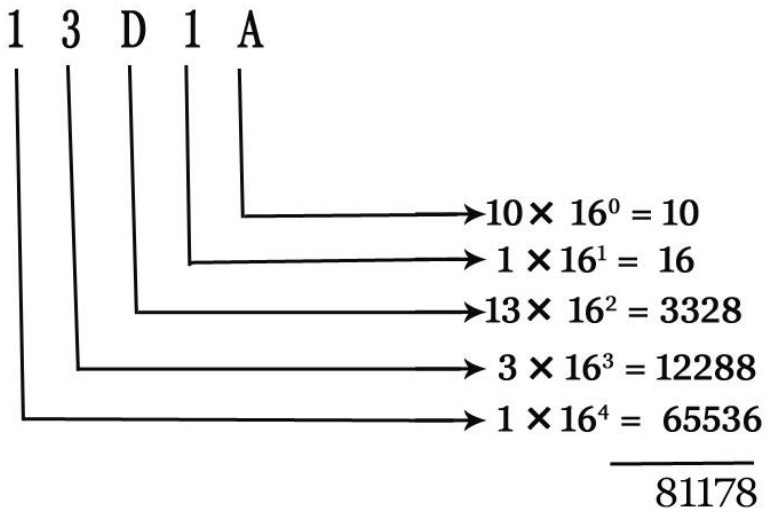


Hexadecimal to Binary, Decimal, Octal Conversions

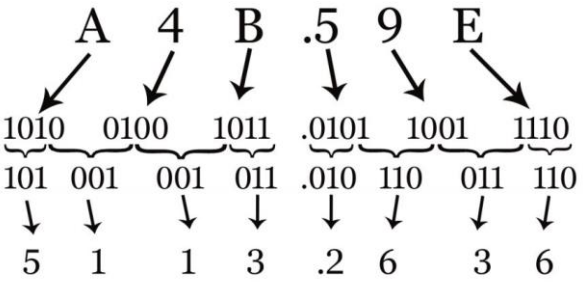
a) Hexadecimal to Binary Conversion



b) Hexadecimal to Decimal Conversion



c) Hexadecimal to Octal Conversion



So, $(A4B.59E)_{16} = (5113.2636)_{8}$

5.5 Binary Addition, Subtraction, Multiplication and Division

The addition and subtraction of the binary number system are similar to that of the decimal number system. The only difference is that the decimal number system consists the digit from 0-9 and their base is 10 whereas the binary number system consists only two digits (0 and 1) which make their operation easier. The addition and subtraction of binary number systems are explained below in details.

For understanding, the binary addition first considers the addition of two decimal numbers as shown below.

$$\begin{array}{r} 3\ \ 4 \\ +\ 5\ \ 7 \\ \hline \end{array}$$

When we added the one's column of the binary digit (i.e., 7+4) we get the number which is greater than the base of the decimal number (the base of the number is 10 and the sum of the digit is 11). Now add the tens column of the binary digit whose sum is equal to 9, and hence less than the base. So there is no carry in the ten's column of the binary digit.

The solution of the above sum is explained below.

$$\begin{array}{r} 1 \\ 3\ \ 4 \\ +\ 5\ \ 7 \\ \hline 9\ \ 1 \\ \hline \end{array}$$

Binary arithmetic is essential part of all the digital computers and many other digital system.

Binary Addition

It is a key for binary subtraction, multiplication, division. There are four rules of binary addition.

Case	A + B	Sum	Carry
1	0 + 0	0	0
2	0 + 1	1	0
3	1 + 0	1	0
4	1 + 1	0	1

In fourth case, a binary addition is creating a sum of (1 + 1 = 10) i.e. 0 is written in the given column and a carry of 1 over to the next column.

Example − Addition

0011010 + 001100 = 00100110

```
  1 1          carry
  0 0 1 1 0 1 0  = 26(10)
+ 0 0 0 1 1 0 0  = 12(10)
-----------------
  0 1 0 0 1 1 0  = 38(10)
```

Binary Subtraction

Subtraction and Borrow, these two words will be used very frequently for the binary subtraction. There are four rules of binary subtraction.

Case	A - B	Subtract	Borrow
1	0 - 0	0	0
2	1 - 0	1	0
3	1 - 1	0	0
4	0 - 1	0	1

Example − Subtraction

0011010 - 001100 = 00001110

```
    1 1        borrow
  0 0 1 1 0 1 0  = 26(10)
- 0 0 0 1 1 0 0  = 12(10)
-----------------
  0 0 0 1 1 1 0  = 14(10)
```

Binary Multiplication

Binary multiplication is similar to decimal multiplication. It is simpler than decimal multiplication because only 0s and 1s are involved. There are four rules of binary multiplication.

Case	A x B	Multiplication
1	0 x 0	0
2	0 x 1	0
3	1 x 0	0
4	1 x 1	1

Example − Multiplication

Example:

0011010 x 001100 = 100111000

$$
\begin{array}{rl}
0\,0\,1\,1\,0\,1\,0 & = 26_{10} \\
\times\, 0\,0\,0\,1\,1\,0\,0 & = 12_{10} \\
\hline
0\,0\,0\,0\,0\,0\,0 & \\
0\,0\,0\,0\,0\,0\,0 & \\
0\,0\,1\,1\,0\,1\,0 & \\
0\,0\,1\,1\,0\,1\,0 & \\
\hline
0\,1\,0\,0\,1\,1\,1\,0\,0\,0 & = 312_{10}
\end{array}
$$

Binary Division

Binary division is similar to decimal division. It is called as the long division procedure.

Example − Division

101010 / 000110 = 000111

$$
\begin{array}{rl}
 & 1\,1\,1 \quad = 7_{10} \\
000110\,\overline{)\,1\,0\,1\,0\,1\,0} & = 42_{10} \\
 -\,1\,1\,0 & = 6_{10} \\
\hline
 1\,0\,0\,1 & \\
 -\,1\,1\,0 & \\
\hline
 1\,1\,0 & \\
 -\,1\,1\,0 & \\
\hline
 0 &
\end{array}
$$

5.6 Boolean algebra

Boolean algebra is a different kind of algebra or rather can be said a new kind of algebra which was invented by world-famous mathematician George Boole in the year of 1854. He published it in his book “An Investigation of the Laws of Thought”.

Later using this technique Claude Shannon introduced a new type of algebra which is termed as Switching Algebra. In digital electronics, there are several methods of simplifying the design of logic circuits. This algebra is one of these methods.

According to George Boole symbols can be used to represent the structure of logical thoughts. This type of algebra deals with the rules or laws, which are known as **laws of Boolean algebra** by which the logical operations are carried out.

There are also few **theorems of Boolean algebra**, that are needed to be noticed carefully because these make calculation fastest and easier. Boolean logic deals with only two variables, 1 and 0 by which all the mathematical operations are to be performed.

Boolean algebra or switching algebra is a system of mathematical logic to perform different mathematical operations in a binary system. There only three basis binary operations, AND, OR, and NOT by which all simple, as well as complex binary mathematical operations, are to be done.

There are many rules in Boolean algebra by which those mathematical operations are done. In Boolean algebra, the variables are represented by English Capital Letter like A, B, C, etc and the value of each variable can be either 1 or 0, nothing else.

In Boolean algebra, an expression given can also be converted into a logic diagram using different logic gates like AND gate, OR gate and NOT gate, NOR gates, NAND gates, XOR gates, XNOR gates, etc.

Some basic logical Boolean operations,

AND Operation

$$0.0 = 0$$
$$0.1 = 0$$
$$1.0 = 0$$
$$1.1 = 1$$

OR Operation

$$0 + 0 = 0$$
$$0 + 1 = 1$$
$$1 + 0 = 1$$
$$1 + 1 = 1$$

Not Operation

$$\overline{1} = 0$$
$$\overline{0} = 1$$

Some basic laws for Boolean Algebra

$$\overline{0} = 1, \overline{1} = 0,\ if\ A = 1\ then\ \overline{A} = 0\ and\ if\ A = 0,\ then\ \overline{A} = 1.$$

A . 0 = 0 where A can be either 0 or 1.

A . 1 = A where A can be either 0 or 1.

A . A = A where A can be either 0 or 1.

A . $\bar{A}$ = 0 where A can be either 0 or 1.

A + 0 = A where A can be either 0 or 1.

A + 1 = 1 where A can be either 0 or 1.

A + $\bar{A}$ = 1

A + A = A

A + B = B + A where A and B can be either 0 or 1.

A . B = B . A where A and B can be either 0 or 1.

The laws of Boolean algebra are also true for more than two variables like,

Cumulative Law for Boolean Algebra

$$A+B+C=A+C+B=B+A+C=B+C+A=C+A+B=C+B+A$$
$$A.B.C=A.C.B=B.A.C=B.C.A=C.A.B=C.B.A$$

According to Cumulative Law, the order of OR operations and AND operations conducted on the variables makes no differences.

Associative Laws for Boolean Algebra

This law is for several variables, where the OR operation of the variables result is the same through the grouping of the variables. This law is quite the same in the case of AND operators.

$$(A+B)+C=A+(B+C)$$
$$(A.B).C=A.(B.C)$$

Distributive Laws for Boolean Algebra

This law is composed of two operators, AND and OR.

$$A.(B+C)=A.B+A.C$$

Let us show one use of this law to prove the expression

$$A+B.C=(A+B).(A+C)$$

Proof:

$$A + B.C = A.1 + B.C \ [Since,\ A.1 = A]$$
$$= A.(1 + B) + B.C \ [Since,\ B + 1 = 1]$$
$$= A.1 + AB + BC$$
$$= A.(1 + C) + AB + BC \ [Since,\ A.A = A.1 = A]$$
$$= A.(A + C) + B.(A + C)$$
$$= (A + B).(A + C)$$

Redundant Literal Rule

$$AA + \overline{A}A + AB + \overline{A}B$$

From the truth table,

Inputs			**Output**
A	B	ĀB	A + ĀB
0	0	0	0
0	1	1	1
1	0	0	1
1	1	0	1

Inputs		**Output**
A	B	A+B
0	0	0
0	1	1
1	0	1
1	1	1

From the truth table, it is proved that,

$$A + \overline{A}B = A + B$$

Similarly,

$$A(\overline{A} + B) = AB$$

Absorption Laws for Boolean Algebra

$$A + A.B = A$$

Proof from truth table,

Inputs			**Output**
A	B	AB	A+A.B
0	0	0	0
0	1	0	0
1	0	0	1
1	1	1	1

Both A and A+A.B column is the same.

$$A + A.B = A(1 + B) = A$$

$$Similarly,\ A(A + B) = A$$

Proof from truth table,

A	**B**	**A+B**	**A.X(A+B)**
0	0	0	0
0	1	1	0
1	0	1	1
1	1	1	1

Both A and A.X or A(A+B) columns are the same.

$$A(A + B) = A.A + AB = A + A.B = A(1 + B) = A$$

From De Morgan's Theorem,

$$\overline{A + B} = \overline{A}\ \overline{B}$$

$$and\ \ \overline{AB} = \overline{A} + \overline{B}$$

Proof from truth table,

Inputs		Outputs			
A	B	$\overline{A+B}$	$\overline{A}.\overline{B}$	$\overline{AB}$	$\overline{A}+\overline{B}$
0	0	1	1	1	1
0	1	0	0	1	1
1	0	0	0	1	1
1	1	0	0	0	0

$Column\ for\ \overline{A+B}\ and\ \overline{A}.\overline{B}\ are\ same.$

$Column\ for\ \overline{AB}\ and\ \overline{A}+\overline{B}\ are\ same.$

5.7 Reduction of Boolean Expressions

Examples of Boolean Algebra

$Simplify,\ \overline{(A+\overline{B})(C+\overline{D})}$

$$Here,\ \overline{(A+\overline{B})(C+\overline{D})}\ [\ As\ per\ De\ Morgan\ Therem\ \overline{x.y}=\overline{x}+\overline{y}\ ]$$
$$=\overline{(A+\overline{B})}\overline{(C+\overline{D})}\ [\ As\ per\ De\ Morgan\ Therem\ \overline{x+y}=\overline{x}.\overline{y}\ ]$$
$$=\overline{A}.\overline{\overline{B}}+\overline{C}.\overline{\overline{D}}$$
$$=\overline{A}B+\overline{C}D$$

These are another method of simplifying a complex Boolean expression. In this method, we only use three simple steps.

1. Complement entire Boolean expression.
2. Change all ORs to ANDs and all ANDs to ORs.
3. Now, complement each of the variables and get the final expression.

By this method,

$\overline{(A+\overline{B})(C+\overline{D})}$ will be first complemented, i.e. $(A+\overline{B})(C+\overline{D})$ .Now, change all (+) to (.) and (.) to (+) i.e. $A\overline{B}+C\overline{D}$. Now, complement each of the variables, $\overline{A}B+\overline{C}D$. This is the final simplified form of a Boolean

expression, $\overline{(A+\overline{B})(C+\overline{D})}$

And it is exactly equal to the results which have been come by applying De Morgan Theorem.

Another example,

$$\overline{\overline{AB}+\overline{A}+AB}=\overline{\overline{AB}}.\overline{\overline{A}}.\overline{\overline{AB}} \quad [Appling\ De\ Morgan\ Therem]$$
$$=AB.A.\overline{\overline{AB}}$$
$$=AB.\overline{\overline{AB}}.A=0$$

By the Second Method,

$$\overline{\overline{AB}}+\overline{A}+AB=\overline{\overline{A+B}}.\overline{A}.A+B=(\overline{\overline{A}+\overline{B}}).A.(\overline{A}+\overline{B})=0$$

$$Example\ simplify,\ AB+A\overline{B}C+B\overline{C}=A(B+\overline{B}C)+B\overline{C}=A(B+\overline{B})(B+C)+B\overline{C}$$
$$=AB+AC+B\overline{C}=AB(C+\overline{C})+AC+B\overline{C}=ABC+AB\overline{C}+AC+B\overline{C}$$
$$=AC(1+B)+B\overline{C}(A+1)=AC+B\overline{C}$$

Representation of Boolean function in the truth table. Let us consider a Boolean function,

$$f(A,B,C)=\overline{A}B+\overline{B}C.$$

Now let us represent the function in the truth table.

A	B	C	$\bar{A}B$	$\bar{B}C$	$\bar{A}B+\bar{B}C$
0	0	0	0	0	0
0	0	1	0	1	1
0	1	0	1	0	1
0	1	1	1	0	1
1	0	0	0	0	0
1	0	1	0	1	1
1	1	0	0	0	0
1	1	1	0	0	0

5.8 Logic Gates

Digital logic gates are the basic building blocks of any digital switching circuit. The input and output relation of a logic gate is based on a certain relationship. Throughout history, logic gates have been implemented using various configurations such as the early RTL (Resistor – Transistor Logic), DTL (Diode – transistor logic), and currently, in use TTL (Transistor-Transistor Logic) which uses PMOS & NMOS CMOS technology to implement boolean functions and logical gates. Logic gates have a wide array of uses such as microprocessors, microcontrollers, embedded system applications, and electronic/electrical circuits.

Classification Digital Logic Gates

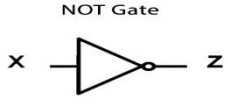
There are seven types of logic gates

- NOT
- AND
- **NAND**
- OR
- NOR
- XOR
- XNOR

NOT Gate

A NOT gate or a Hex inverter is a digital logic gate that inverts the input digital signal. In other words, a NOT Gate performs logical negation. A NOT gate always has high or logic level 1 output when its input is low or at logic level 0. On the other hand, a logical NOT gate always has low or logic level 0 output when input is high or at logic level 1.

Symbol



Truth Table

Not Gate Truth Table

Input	Output
0	1
1	0

Boolean Representation

X=Z' Where X is input & Z is output

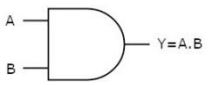
Here, the truth table and the Boolean expression indicate that when the input to the NOT gate is True or 1 if the output will be False or 0. Similarly, when the input to the NOT gate is False or 0, the output of the NOT gate will be true or 1.

AND Gate

An AND Gate is a logical operator/circuit that gives a logical high (1) output only when **all** of its inputs are high (1), otherwise, it results in a logical low (0). It is one of the most common logic gates used in the construction of memory circuits used in computing systems.

Symbol

AND Gate



Truth Table

AND Gate Truth Table

Input		Output
A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

Boolean Representation

A.B=Y Where A & B are inputs & Y is output.

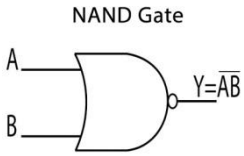
The above truth table and the boolean expression indicate that in order for the

output of an AND digital logic gate to be HIGH, All the inputs to the gate must be high. If any input of the AND gate is LOW then the output of the AND gate will be LOW.

NAND Gate

A NAND Gate is a logical gate which is a combination of AND and NOT gates. It is considered a "universal" gate in Boolean algebra as it is capable of producing all other logic gates. A NAND gate consists of one or more inputs with a single output. The output of the NAND gate is always at logic 1 and only goes to logic 0 when all the inputs to the NAND gate are at logic 1. In other words, the output of the NAND gate always remains true if at least one of its inputs remains false.

Symbol



Truth Table

NAND Gate Truth Table

Input		Output
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

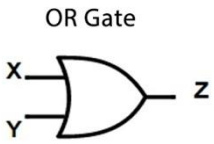
Boolean Representation

A'.B'=Y Where A & B are inputs & Y is output.

OR Gate

An OR gate consists of one or more inputs, but with only a single output. The output of an OR gate is true (or 1) if at least one of the inputs is true or 1. In other words, unless all inputs are 0, the output of the OR gate is always 1. The function of an OR gate is complementary to an AND gate, with the latter finding the minimum of the binary inputs and the former finding the maximum between the binary inputs.

Symbol



Truth Table

OR Gate Truth Table

Input		Output
X	Y	Z
0	0	0
0	1	1
1	0	1
1	1	1

Boolean Representation

X+Y=Z Where X & Y are inputs & Z is output.

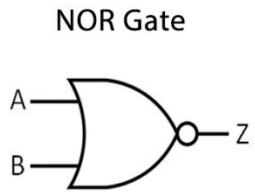
The above truth table and the boolean expression indicates that in order for the output of the OR gate to be **HIGH**. At least one of the inputs to the OR gate must be high. If all the inputs to the OR gate are LOW then the Output of the gate will be LOW.

NOR Gate

An OR gate followed by a NOT gate in a cascaded condition is called a NOR gate. The inclusive NOR (Not – OR) gate has an output that is normally at logic level "1" and only goes "LOW" to a logic level "0" when **any** of its inputs are at logic level "1". The Logic NOR Gate is the reverse or complementary form of

the inclusive OR gate.

Symbol



Truth Table

NOR Gate Truth Table

Input		Output
A	B	Z
0	0	1
0	1	0
1	0	0
1	1	0

Boolean Representation

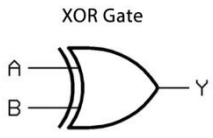
A+B=Z' Where A & B are inputs & Z is output

The above truth table and the boolean expression indicates that in order for the output of the NOR gate to be **LOW**. At least one of the inputs to the NOR gate must be HIGH. If all the inputs to the NOR gate are LOW then the Output of the gate will be HIGH.

XOR Gate

A **XOR gate** is a digital logic gate that gives a true (1 or HIGH) output when the number of true inputs is odd. An XOR gate implements an exclusive OR; meaning true output results if one, and only one, of the inputs to the gate is true. If both inputs are false (0/LOW) or both are true, a false output results.

Symbol



Truth Table

XOR Gate Truth Table

Input		Output
A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

Boolean Representation

A⊕B=Y Where A & B are inputs & Y is output

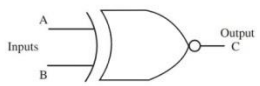
The above truth table and boolean expression indicate that in order to yield a HIGH output from the XOR logic gate, only one (1) of all the inputs to the gate must be high. If there are more than one high inputs to the XOR logic gate, then the output will be LOW.

XNOR Gate

XNOR Gate is a type of digital logic gate that receives two inputs and produces one output. All inputs are treated with the same logic, responding equally to similar inputs. It is also known as an 'Equivalence Gate'. If all inputs to the XNOR gate are 0, the gate will produce a 1. If all inputs are 1, the gate will also produce a 1. However, if any input to the gate differs from the other, the gate will output a 0.

Symbol

XNOR Gate



Truth Table

XNOR Gate Truth Table

Input		Output
A	B	C
0	0	1
0	1	0
1	0	0
1	1	1

Boolean Representation

A⊙B=C' Where A & B are inputs & C is output

Here, the truth table and the boolean expression indicates that in order tp yield a LOW output put from the XNOR gate the inputs should be dissimilar from each other (either 1 or 0). If all the inputs to the XNOR gate are same (1 or 0), the XNOR gate will always yield HIGH or 1 output.

Applications

Digital Logic Gates have a wide array of applications.

- Generally used in circuits such as dynamic memory circuits, switching circuits, and signal conditioning circuits.
- Also used in simple trainer boards to simulate gate switching for academic purposes.
- Serve as the basic building blocks for many digital consumer products such as smartphones, PCs, and laptops, etc.

5.9 De-Morgan's Theorem

A famous mathematician **De-Morgan** invented the two most important theorems of boolean algebra. The De-Morgan's theorems are used for mathematical verification of the equivalency of the NOR and negative-AND gates and the negative-OR and NAND gates. These theorems play an important role in solving various boolean algebra expressions. In the below table, the logical operation for each combination of the input variable is defined.

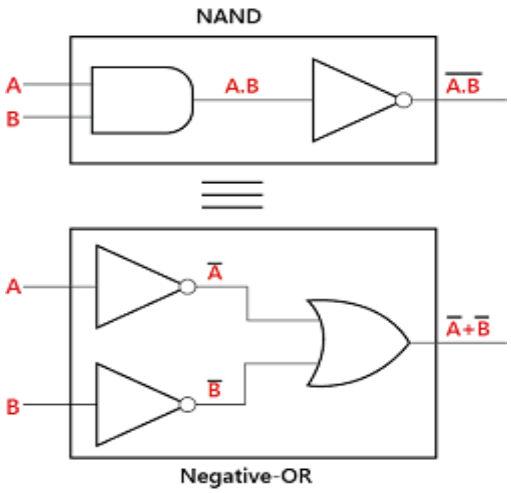
Input variables		**Output Condition**			
A	**B**	**AND**	**NAND**	**OR**	**NOR**
0	0	0	1	0	1
0	1	0	1	1	0
1	0	0	1	1	0
1	1	1	0	1	0

The rules of De-Morgan's theorem are produced from the Boolean expressions for OR, AND, and NOT using two input variables x and y. The first theorem of Demorgan's says that if we perform the AND operation of two input variables and then perform the NOT operation of the result, the result will be the same as the OR operation of the complement of that variable. The second theorem of DeMorgan says that if we perform the OR operation of two input variables and then perform the NOT operation of the result, the result will be the same as the AND operation of the complement of that variable.

De-Morgan's First Theorem

According to the first theorem, the complement result of the AND operation is equal to the OR operation of the complement of that variable. Thus, it is equivalent to the NAND function and is a negative-OR function proving that (A.B)' = A'+B' and we can show this using the following table.

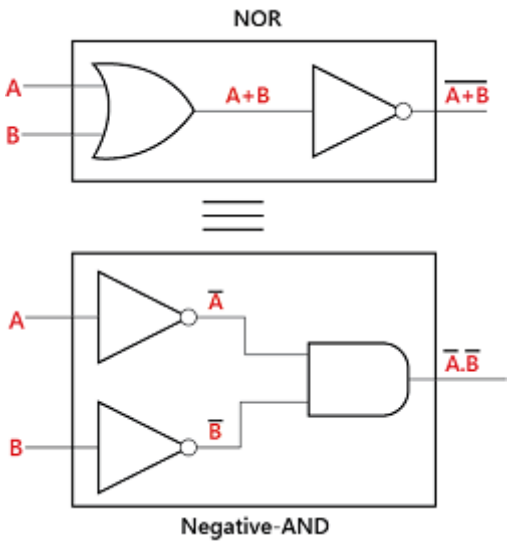
Inputs		**Output For Each Term**				
A	**B**	**A.B**	**(A.B)'**	**A'**	**B'**	**A'A+B'**
0	0	0	1	1	1	1
0	1	0	1	1	0	1
1	0	0	1	0	1	1
1	1	1	0	0	0	0



De-Morgan's Second Theorem

According to the second theorem, the complement result of the OR operation is equal to the AND operation of the complement of that variable. Thus, it is the equivalent of the NOR function and is a negative-AND function proving that (A+B)' = A'.B' and we can show this using the following truth table.

Inputs		Output For Each Term				
A	**B**	**A+B**	**(A+B)'**	**A'**	**B'**	**A'.B'**
0	0	0	1	1	1	1
0	1	1	0	1	0	0
1	0	1	0	0	1	0
1	1	1	0	0	0	0



Let's take some examples in which we take some expressions and apply DeMorgan's theorems.

Example 1: (A.B.C)'

(A.B.C)'=A'+B'+C'

Example 2: (A+B+C)'

(A+B+C)'=A'.B'.C

Example 3: ((A+BC')'+D(E+F')')'

For applying the DeMorgan's theorem on this expression, we have to follow the following expressions:

1) In complete expression, first, we find those terms on which we can apply the DeMorgan's theorem and treat each term as a single variable.

$$\overline{A + B\,\overline{C}} = X$$

$$D(\overline{E + \overline{F}}) = Y$$

So,

$$(\overline{A + B\,\overline{C}}) + D(\overline{E + \overline{F}}) = \overline{X + Y}$$

2) Next, we apply DeMorgan's first theorem. So,

$$\overline{X + Y} = \overline{X} + \overline{Y}$$

$$(\overline{A + B\,\overline{C}}) + D(\overline{E + \overline{F}}) = (\overline{(A + B\,\overline{C})}) \cdot (\overline{D(\overline{E + \overline{F}})})$$

3) Next, we use rule number 9, i.e., (A=(A')') for canceling the double bars.

$$(\overline{(A + B\,\overline{C})}) \cdot (\overline{D(\overline{E + \overline{F}})}) = (A + B\overline{C})(\overline{D(\overline{E+F})})$$

4) Next, we apply DeMorgan's second theorem. So,

$$(A + B\overline{C})(\overline{D(\overline{E+F})}) = (A + B\,\overline{C})\,(\overline{D} + \overline{(\overline{E + F})})$$

5) Again apply rule number 9 to cancel the double bar

$$(A + B\,\overline{C})\,(\overline{D} + \overline{(\overline{E + F})}) = (A+B\,\overline{C})\,(\overline{D} + E + F)$$

Now, this expression has no term in which we can apply any rule or theorem. So, this is the final expression.

Example 4: (AB'.(A + C))'+ A'B.(A + B + C')'

$$\overline{A\,\bar{B}.(A+C)} + \bar{A}\,B.\overline{(A+B+\bar{C})}$$

$$\overline{A\,\bar{B}.(A+C)} + \bar{A}\,B.\overline{(A+B+\bar{C})} = \overline{A\,\bar{B}} + \overline{A+C} + \bar{A}\,B\,.\,(\bar{A}\,.\,\bar{\bar{B}}\,.\,\bar{\bar{C}})$$

$$\overline{A\,\bar{B}} + \overline{A+C} + \bar{A}\,B\,.\,(\bar{A}\,.\,\bar{\bar{B}}\,.\,\bar{\bar{C}}) = (\bar{A}+\bar{\bar{B}}) + \bar{A}\,.\,\bar{C} + \bar{A}\,\bar{A}\,B\,B\,C$$

$$(\bar{A}+\bar{\bar{B}}) + \bar{A}\,.\,\bar{C} + \bar{A}\,\bar{A}\,B\,B\,C = \bar{A} + B + \bar{A}\,\bar{C} + \bar{A}\,B\,C$$

$$\bar{A} + B + \bar{A}\,\bar{C} + \bar{A}\,B\,C = \bar{A}\,(1+\bar{C}) + B + \bar{A}\,B\,C$$

$$\bar{A}\,(1+\bar{C}) + B + \bar{A}\,B\,C = \bar{A} + B + \bar{A}\,B\,C$$

$$\bar{A} + B + \bar{A}\,B\,C = \bar{A} + B(1+\bar{A}\,C)$$

$$\bar{A} + B(1+\bar{A}\,C) = \bar{A} + B$$

5.10 Adder and Subtractor

In digital electronics, an adder is a circuit that performs the addition of two binary numbers. A subtractor is a circuit that performs the subtraction of two binary numbers. Both adders and subtractors can be implemented using logic gates such as AND, OR, and NOT gates.

A half adder is the simplest type of adder, which can add two single-digit binary numbers and produce a sum and a carry output. A half adder can be implemented using an XOR gate and an AND gate.

A full adder is a more complex adder that can add two binary digits along with a carry input and produce a sum and a carry output. A full adder can be implemented using two half adders and an OR gate.

A subtractor can be implemented using an adder and an additional input, which is the 2's complement of the number being subtracted. The 2's complement of a binary

number is obtained by inverting all the bits and adding 1 to the result.

In summary, adders and subtractors can be implemented using various combinations of logic gates depending on their complexity and requirements.

Design of Half Adders and Full Adders:

- A combinational logic circuit that performs the addition of two single bits is called Half Adder.
- A combinational logic circuit that performs the addition of three single bits is called Full Adder.

1. Half Adder:

- It is a arithmetic combinational logic circuit designed to perform addition of two single bits.
- It contain two inputs and produces two outputs.
- Inputs are called Augend and Added bits and Outputs are called Sum and Carry.

Let us observe the **addition of single bits**,

0+0=0

0+1=1

1+0=1

1+1=10

Since 1+1=10, the result must be two bit output. So, Above can be rewritten as,

0+0=00

0+1=01

1+0=01

1+1=10

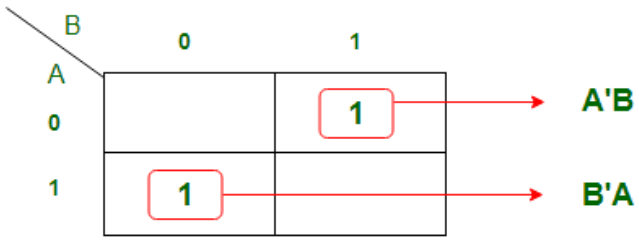
The result of 1+1 is 10, where '1' is carry-output (C_{out}) and '0' is Sum-output (Normal Output).

Truth Table of Half Adder:

Inputs		Outputs	
A	B	Sum	Carry
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

Next Step is to draw the Logic Diagram. To draw Logic Diagram, We need Boolean Expression, which can be obtained using K-map (karnaugh map). Since there are two output variables 'S' and 'C', we need to define K-map for each output variable.

K-map for output variable Sum 'S':



A'B+B'A=A xor B

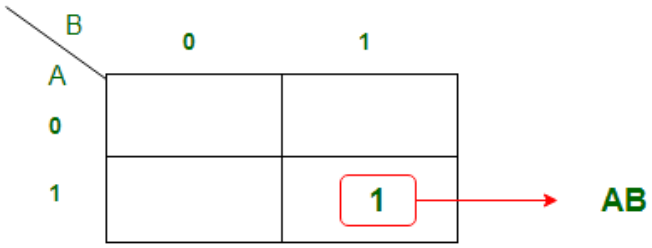
K-map is of **Sum of products** form. The equation obtained is

S = AB' + A'B

which can be logically written as,

S = A xor B

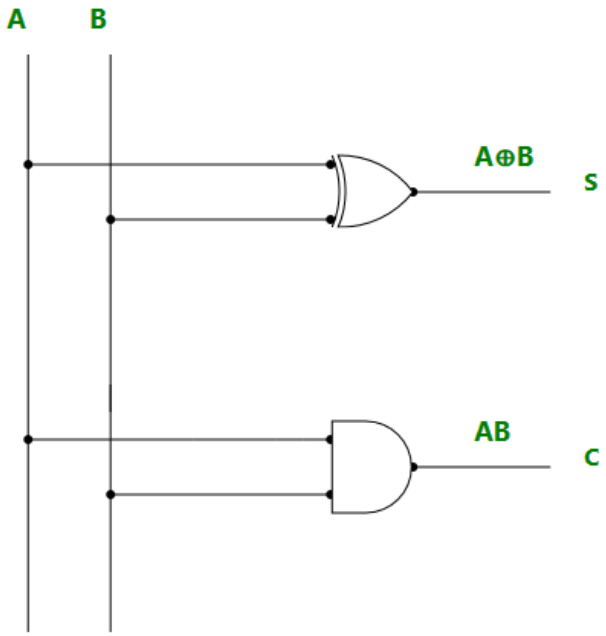
K-map for output variable Carry 'C':



The equation obtained from K-map is,

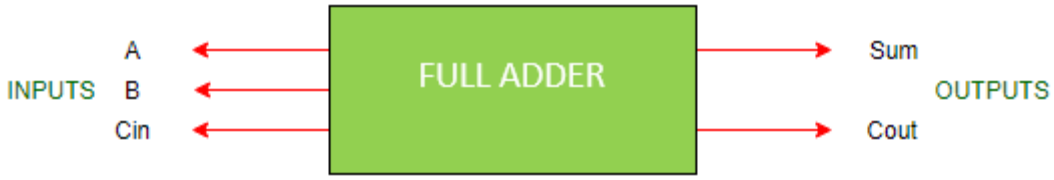
C = AB

Using the Boolean Expression, we can draw logic diagram as follows..



Limitations: Adding of Carry is not possible in Half adder.

2. Full Adder:

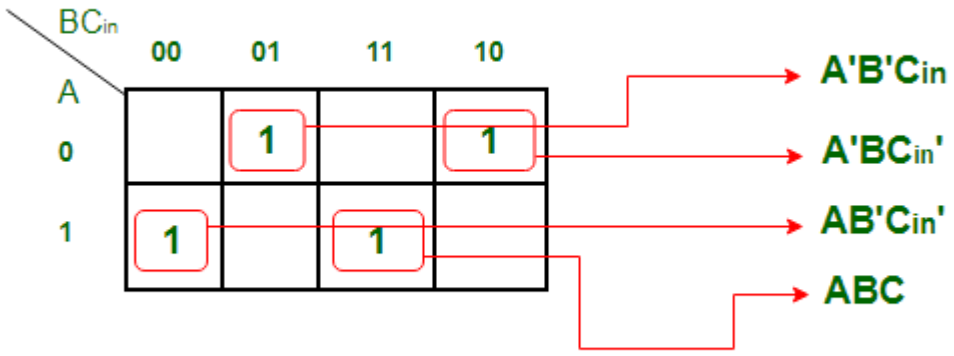


- To overcome the above limitation faced with Half adders, Full Adders are implemented.
- It is a arithmetic combinational logic circuit that performs addition of three single bits.
- It contains three inputs (A, B, C_{in}) and produces two outputs (Sum and C_{out}).
- Where, C_{in} -> Carry In and C_{out} -> Carry Out

Truth table of Full Adder:

Inputs			Outputs	
A	B	C_{in}	Sum	C_{out}
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

K-map Simplification for output variable Sum 'S':



The equation obtained is,

$S = A'B'C_{in} + AB'C_{in}' + ABC + A'BC_{in}'$

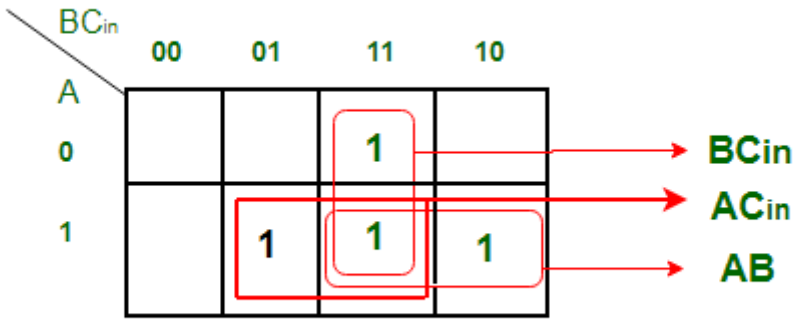
The equation can be simplified as,

$S = B'(A'C_{in}+AC_{in}') + B(AC + A'C_{in}')$

$S = B'(A \text{ xor } C_{in}) + B (A \text{ xor } C_{in})'$

$S = A \text{ xor } B \text{ xor } C_{in}$

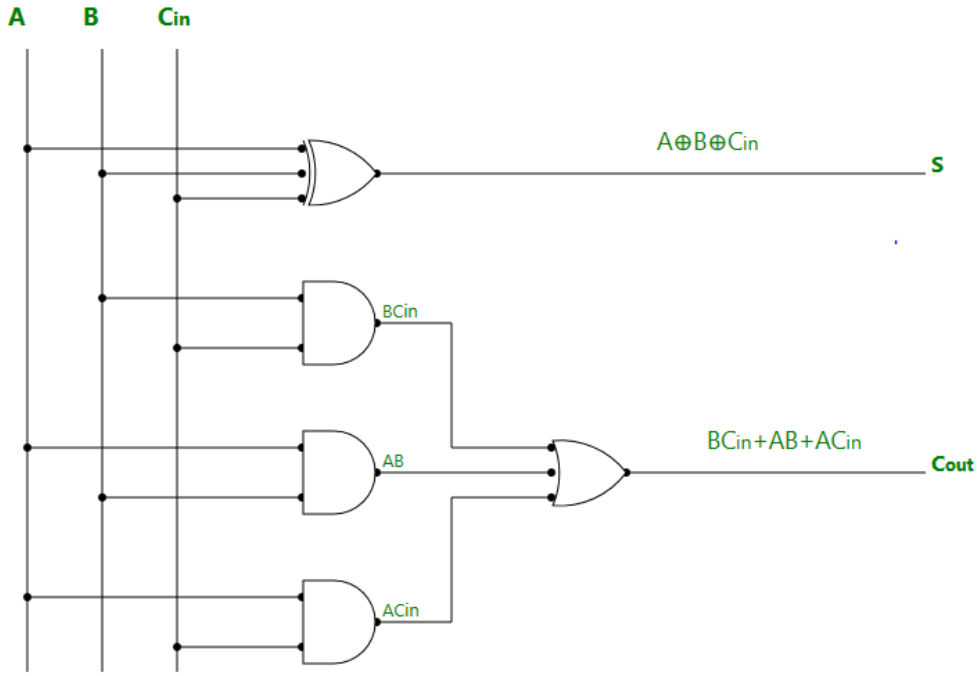
K-map Simplification for output variable 'C_{out}'



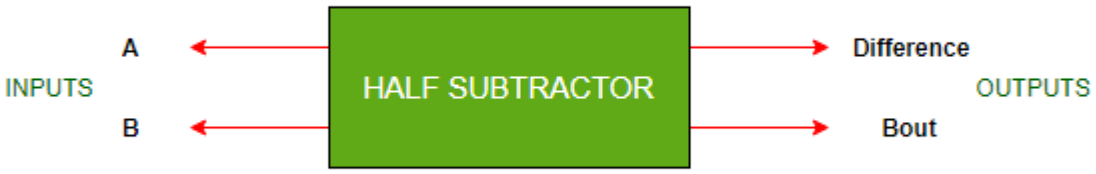
The equation obtained is,

$C_{out} = BC_{in} + AB + AC_{in}$

Logic Diagram of Full Adder:



3. Half Subtractor:

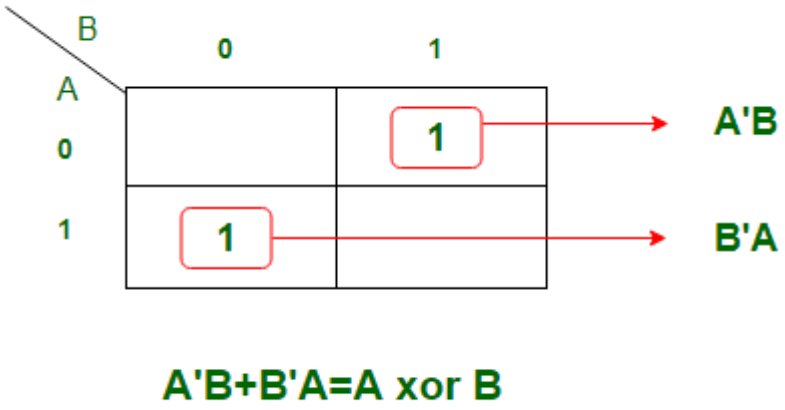


- It is a combinational logic circuit designed to perform the subtraction of two single bits.
- It contains two inputs (A and B) and produces two outputs (Difference and Borrow-output).

Truth Table of Half Subtractor:

Inputs		Outputs	
A	B	D	B_o
0	0	0	0
0	1	1	1
1	0	1	0
1	1	0	0

K-map Simplification for output variable 'D':



A'B+B'A=A xor B

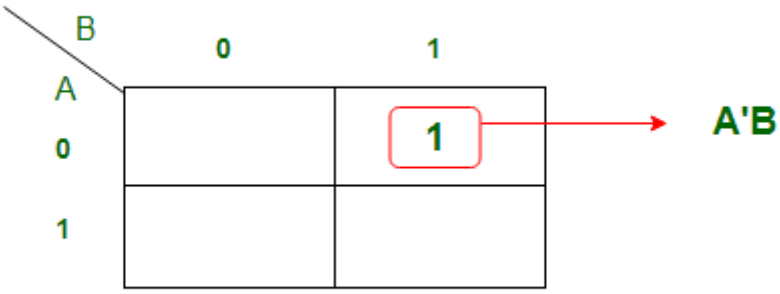
The equation obtained is,

D = A'B + AB'

which can be logically written as,

D = A xor B

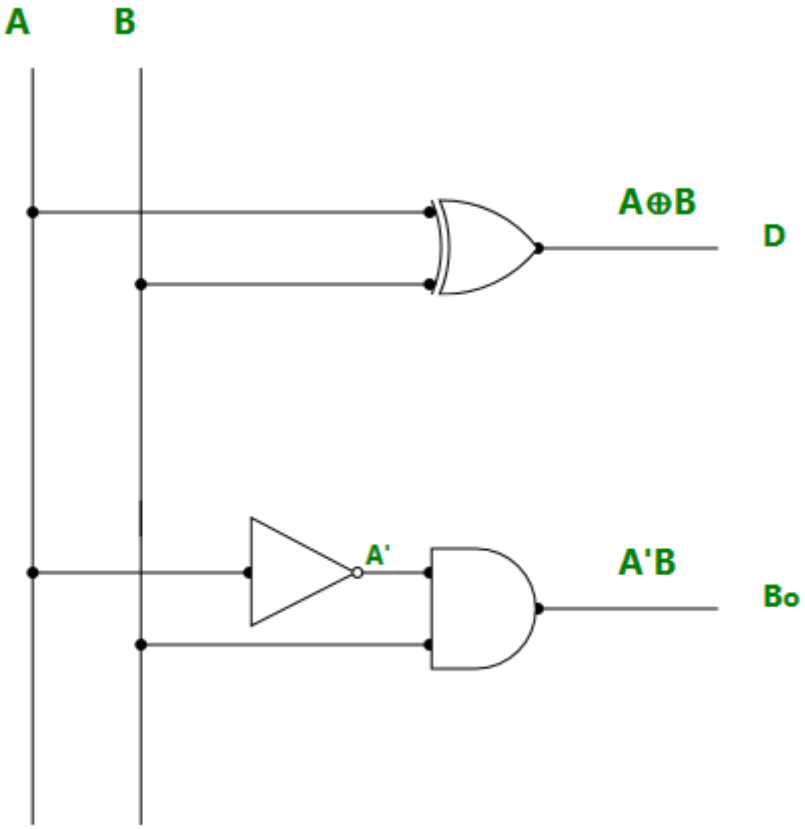
K-map Simplification for output variable 'B_{out}' :



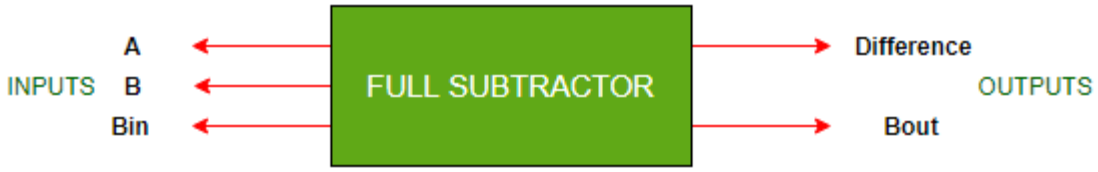
The equation obtained from above K-map is,

B_{out} = A'B

Logic Diagram of Half Subtractor:



4. Full Subtractor:

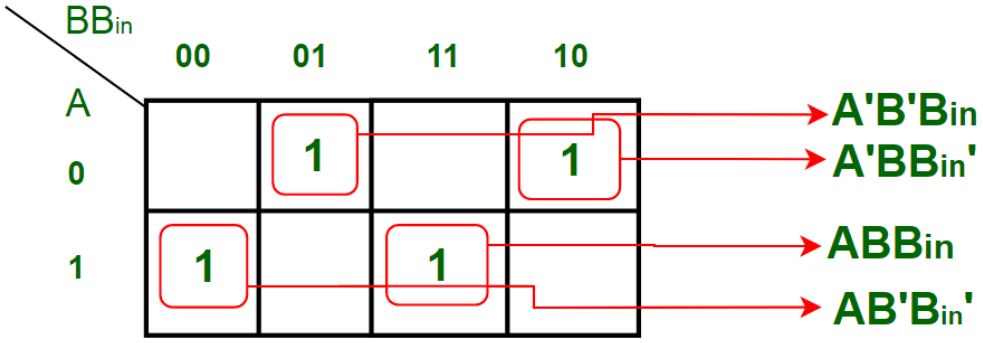


- It is a Combinational logic circuit designed to perform subtraction of three single bits.
- It contains three inputs(A, B, B_{in}) and produces two outputs (D, B_{out}).
- Where, A and B are called **Minuend** and **Subtrahend** bits.
- And, B_{in} -> Borrow-In and B_{out} -> Borrow-Out

Truth Table of Full Subtractor:

Inputs			Outputs	
A	B	B_{in}	D	B_{out}
0	0	0	0	0
0	0	1	1	1
0	1	0	1	1
0	1	1	0	1
1	0	0	1	0
1	0	1	0	0
1	1	0	0	0
1	1	1	1	1

K-map Simplification for output variable 'D' :



The equation obtained from above K-map is,

$D = A'B'B_{in} + AB'B_{in}' + ABB_{in} + A'BB_{in}'$

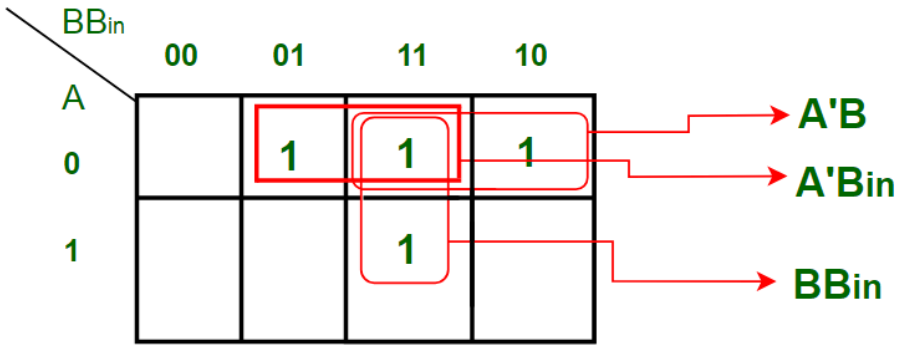
which can be simplified as,

$D = B'(A'B_{in} + AB_{in}') + B(AB_{in} + A'B_{in}')$

$D = B'(A \text{ xor } B_{in}) + B(A \text{ xor } B_{in})'$

$D = A \text{ xor } B \text{ xor } B_{in}$

K-map Simplification for output variable 'B_{out}' :

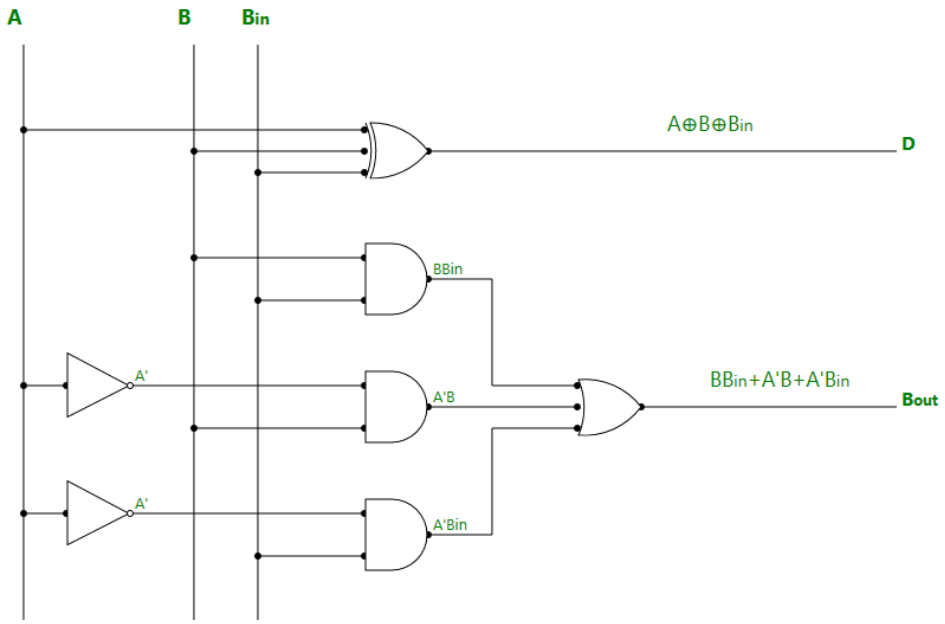


The equation obtained is,

$B_{out} = BB_{in} + A'B + A'B_{in}$

Logic Diagram of Full

Subtractor:



Applications:

1. For performing arithmetic calculations in electronic calculators and other digital devices.
2. In Timers and Program Counters.
3. Useful in Digital Signal Processing.

Chapter 6
Measuring Instruments

Introduction to Measurement and Instrumentation – SI Systems – Methods of Measurement – Static and Dynamic – Characteristics of Instruments – Definitions: True value – Accuracy – Error – Precision – Sensitivity – Resolution – Types and Operating Principles of Measuring Instruments – Moving Coil – Moving Iron – Principle of Energy Meter

6.1 Introduction to Measurement and Instrumentation

Measurement and instrumentation are essential components of engineering, science, and technology. The purpose of measurement is to obtain quantitative information about physical properties or variables, while instrumentation refers to the devices or systems used to measure, record, and control these variables.

Instruments can be classified based on the physical quantity they measure, such as temperature, pressure, flow, level, or electrical parameters like voltage, current, and resistance. Instruments can also be classified based on their principle of operation, such as mechanical, electrical, optical, or thermal.

Measurement and instrumentation are used in various applications, such as process control, automation, quality control, and research and development. They play a critical role in ensuring the accuracy and reliability of data, and they help to optimize processes, increase efficiency, and reduce costs.

Some common types of instruments include:

1. Thermometers for temperature measurement
2. Pressure gauges for pressure measurement
3. Flowmeters for flow measurement
4. Level sensors for level measurement
5. Voltmeters for voltage measurement
6. Ammeters for current measurement
7. Oscilloscopes for measuring and analyzing electrical signals
8. Spectrum analyzers for measuring and analyzing frequency and power spectra.

In addition to measuring physical variables, instrumentation can also include control systems that use feedback to adjust and maintain the desired variable at a specified value or range. Control systems are widely used in industrial and process control applications to regulate and optimize production processes.

Overall, measurement and instrumentation are fundamental tools for understanding and manipulating the physical world, and they play a critical role in many areas of engineering and science.

6.2 SI Systems

The International System of Units (SI) is a metric system of measurement that is widely used in scientific and engineering fields. The SI system was first introduced in 1960 and is based on seven base units, which are used to define all other units of measurement:

1. Meter (m) - for length
2. Kilogram (kg) - for mass
3. Second (s) - for time
4. Ampere (A) - for electric current
5. Kelvin (K) - for temperature
6. Mole (mol) - for amount of substance

7. Candela (cd) - for luminous intensity

In addition to the base units, there are a number of derived units that are used to express measurements of other physical quantities. For example, the unit of force is the Newton (N), which is defined as the force required to accelerate a mass of one kilogram at a rate of one meter per second squared.

The SI system is designed to be a coherent system of units, which means that units of different physical quantities can be combined algebraically to form new units. For example, the unit of energy is the Joule (J), which is equal to one Newton-meter. This allows for easy conversion between units and simplifies calculations.

The SI system is widely used in scientific and engineering fields because it provides a consistent and universally recognized system of measurement. It is also easy to use and understand, with a clear and logical structure.

6.3 Methods of Measurement

There are various methods of measurement used in scientific, engineering, and industrial applications, depending on the physical quantity being measured and the level of accuracy required. Here are some of the most common methods of measurement:

1. **Direct Measurement:** This is the most straightforward method of measurement, where the quantity is directly measured using an instrument, such as a ruler, a weighing scale, or a thermometer.

2. **Indirect Measurement:** This method involves measuring other physical quantities that are related to the quantity being measured, and then using mathematical equations to calculate the value of the desired quantity. For example, the volume of a container can be indirectly measured by measuring

its dimensions and using the formula for the volume of a rectangular prism.

3. **Comparative Measurement:** This method involves comparing the quantity being measured with a standard reference or a known value. For example, the accuracy of a thermometer can be verified by comparing it with a calibrated thermometer that has a known accuracy.

4. **Null Measurement:** This method involves balancing the quantity being measured against another known quantity, such as a known weight or a known voltage, until the two quantities are equal. This can be used to measure very small quantities with high precision.

5. **Optical Measurement:** This method uses light or other electromagnetic radiation to measure the physical properties of an object, such as its size, shape, or position. Optical measurement techniques include microscopy, interferometry, and spectroscopy.

6. **Electrical Measurement:** This method uses electrical signals to measure physical quantities such as voltage, current, resistance, and capacitance. Electrical measurement techniques include multimeters, oscilloscopes, and network analyzers.

7. **Magnetic Measurement:** This method uses magnetic fields to measure physical quantities such as magnetic field strength, magnetic flux, and magnetic susceptibility. Magnetic measurement techniques include magnetometers and magnetic resonance imaging (MRI).

Overall, the choice of measurement method depends on the physical quantity being measured, the accuracy required, and the available instrumentation and expertise.

6.4 Static Characteristics of Instruments

Static characteristics of instruments refer to their ability to provide accurate and reliable measurements of a physical quantity that is constant over time. These characteristics are determined when the instrument is in a steady state, and no changes occur in the measured quantity. Here are some of the most important static characteristics of instruments:

1. **Accuracy:** Accuracy refers to the degree to which an instrument's measured value corresponds to the true value of the quantity being measured. It is usually expressed as a percentage of the true value, and it depends on the type of instrument, the calibration method, and the environmental conditions.

2. **Precision:** Precision refers to the degree to which an instrument's repeated measurements of the same quantity are close to each other. It is usually expressed as a percentage of the average value of the measurements, and it depends on the type of instrument, the measurement method, and the environmental conditions.

3. **Sensitivity:** Sensitivity refers to the ability of an instrument to detect small changes in the measured quantity. It is usually expressed as the ratio of the change in the measured quantity to the change in the instrument's output signal, and it depends on the type of instrument, the measurement method, and the environmental conditions.

4. **Linearity:** Linearity refers to the ability of an instrument to provide a linear relationship between the measured quantity and its output signal. A linear instrument provides a straight-line response to changes in the measured quantity, whereas a nonlinear instrument provides a curved response.

5. **Hysteresis:** Hysteresis refers to the difference in the output signal of an instrument for increasing and decreasing values of the measured quantity. This is due to the instrument's internal mechanisms, such as friction or magnetic properties, and it can affect the accuracy and precision of the measurements.

6. **Repeatability:** Repeatability refers to the ability of an instrument to provide consistent measurements of the same quantity under the same conditions over time. It is usually expressed as the maximum difference between repeated measurements, and it depends on the type of instrument, the measurement method, and the environmental conditions.

7. **Reproducibility:** Reproducibility refers to the ability of an instrument to provide consistent measurements of the same quantity under different conditions over time. It is usually expressed as the maximum difference between measurements taken by different instruments or operators, and it depends on the type of instrument, the measurement method, and the environmental conditions.

In summary, the static characteristics of an instrument are crucial in determining its accuracy, precision, sensitivity, linearity, hysteresis, repeatability, and reproducibility. These characteristics must be considered carefully when selecting an instrument for a particular application, and they must be regularly calibrated and maintained to ensure the instrument's continued accuracy and reliability.

6.5 Dynamic Characteristics of Instruments

Dynamic characteristics of instruments refer to their ability to provide accurate and reliable measurements of a physical quantity that is changing over time. These characteristics are determined when the instrument is subjected to changes in the measured quantity. Here are some of the most important dynamic

characteristics of instruments:

1. **Rise time:** Rise time is the time taken by an instrument to respond to a sudden change in the measured quantity. It is usually expressed as the time taken for the instrument's output signal to rise from 10% to 90% of its steady-state value. A fast rise time indicates a responsive instrument, which can capture sudden changes in the measured quantity accurately.

2. **Settling time:** Settling time is the time taken by an instrument to settle down and provide a stable reading after a sudden change in the measured quantity. It is usually expressed as the time taken for the instrument's output signal to settle within a specified tolerance band of its steady-state value. A short settling time indicates an instrument that is quick to provide stable readings after changes in the measured quantity.

3. **Bandwidth:** Bandwidth is the range of frequencies of the measured quantity that an instrument can measure accurately. It is usually expressed as the maximum frequency at which the instrument's output signal is within a specified tolerance band of the true value of the measured quantity. A wide bandwidth indicates an instrument that can measure rapidly changing quantities accurately.

4. **Overload recovery time:** Overload recovery time is the time taken by an instrument to recover from an overload condition and provide accurate measurements again. It is usually expressed as the time taken for the instrument's output signal to settle within a specified tolerance band of its steady-state value after an overload condition has occurred.

5. **Dynamic range:**Range of values of the measured quantity that an instrument can measure accurately. It is usually expressed as the ratio of the maximum

measurable value to the minimum measurable value. A wide dynamic range indicates an instrument that can measure a broad range of values accurately.

6. **Sensitivity to vibration and shock:** Sensitivity to vibration and shock refers to the degree to which an instrument's output signal is affected by external mechanical disturbances. A high sensitivity to vibration and shock can result in measurement errors, especially in applications where the instrument is subject to mechanical vibrations or shocks.

In summary, the dynamic characteristics of an instrument are crucial in determining its ability to provide accurate and reliable measurements of rapidly changing quantities. These characteristics must be considered carefully when selecting an instrument for a particular application, and they must be regularly calibrated and maintained to ensure the instrument's continued accuracy and reliability.

6.6 Definitions

Here are the definitions of some key terms related to measurement and instrumentation:

1. **True value:** The true value of a measured quantity is the actual or exact value of that quantity. In practice, it is often impossible to determine the true value precisely, so we use measurements to estimate it.

2. **Accuracy:** Accuracy refers to how closely a measured value agrees with the true value of a quantity. An accurate measurement is one that is close to the true value, while an inaccurate measurement is one that is far from the true value.

3. **Error:** Error is the difference between the measured value and the true value

of a quantity. A positive error means the measured value is higher than the true value, while a negative error means the measured value is lower than the true value.

4. **Precision:** Precision refers to how closely repeated measurements of a quantity agree with each other. A precise measurement is one that has a low amount of variation between repeated measurements, while an imprecise measurement has a high amount of variation.

5. **Sensitivity:** Sensitivity is the degree to which an instrument's output changes in response to changes in the measured quantity. A sensitive instrument has a large output change for a small change in the measured quantity, while an insensitive instrument has a small output change for the same change in the measured quantity.

6. **Resolution:** Resolution refers to the smallest detectable change in the quantity being measured. It is the smallest increment of the quantity that can be detected by the instrument. A high-resolution instrument can detect small changes in the quantity, while a low-resolution instrument cannot.

In summary, understanding these terms is essential in evaluating the performance of an instrument and ensuring the accuracy and reliability of measurements.

6.7 Types of Measuring Instruments

There are various types of measuring instruments available, and they can be categorized based on the physical quantity they measure, their working principles, and their applications. Here are some of the most common types of measuring instruments:

1. **Ammeters:** Ammeters are instruments used to measure the flow of electric

current in a circuit. They are typically connected in series with the circuit and have a low resistance to minimize the voltage drop across the ammeter.

2. **Voltmeters:** Voltmeters are instruments used to measure the electric potential difference between two points in a circuit. They are typically connected in parallel with the circuit and have a high resistance to avoid drawing significant current from the circuit.

3. **Multimeters:** Multimeters are versatile instruments that can measure various electrical quantities such as voltage, current, resistance, capacitance, and frequency. They can be digital or analog and are widely used in electrical and electronics applications.

4. **Oscilloscopes:** Oscilloscopes are instruments used to visualize and analyze the waveform of an electrical signal. They can display the amplitude, frequency, and phase of the signal and are used in various applications, including signal analysis, circuit debugging, and testing.

5. **Thermometers:** Thermometers are instruments used to measure temperature. They can be of various types, including liquid-in-glass, bimetallic, thermocouple, and resistance temperature detectors (RTDs). They are used in many applications, including heating, ventilation, and air conditioning (HVAC) systems, medical devices, and food processing.

6. **Pressure gauges:** Pressure gauges are instruments used to measure the pressure of fluids or gases. They can be of various types, including mechanical, electronic, and digital. They are used in many applications, including industrial processes, aerospace, and automotive.

7. **Flow meters:** Flow meters are instruments used to measure the rate of flow

of fluids or gases. They can be of various types, including turbine, ultrasonic, electromagnetic, and thermal. They are used in many applications, including water treatment, oil and gas, and HVAC systems.

8. **Spectrometers:** Spectrometers are instruments used to measure the spectral properties of light. They can be of various types, including UV-Vis, infrared, and mass spectrometers. They are used in many applications, including material analysis, environmental monitoring, and medical diagnosis.

In summary, there are various types of measuring instruments available, and selecting the right one for a particular application requires careful consideration of the physical quantity being measured, the instrument's working principle, and its accuracy and reliability.

6.8 Operating Principles of Measuring Instruments

Measuring instruments operate based on various principles, and the operating principle determines the accuracy, reliability, and sensitivity of the instrument. Here are some of the most common operating principles of measuring instruments:

1. **Mechanical principle:** Measuring instruments based on mechanical principles use mechanical components such as springs, levers, and linkages to convert the measured quantity into a readable output. Examples of instruments that use mechanical principles include spring scales, weighing scales, and mechanical pressure gauges.

2. **Electrical principle:** Measuring instruments based on electrical principles use the electrical properties of materials such as resistance, capacitance, and inductance to convert the measured quantity into an electrical signal that can be displayed or recorded. Examples of instruments that use electrical principles include voltmeters, ammeters, and multimeters.

3. **Optical principle:** Measuring instruments based on optical principles use the properties of light to measure the physical quantity. Examples of instruments that use optical principles include spectrometers, interferometers, and optical microscopes.
4. **Magnetic principle:** Measuring instruments based on magnetic principles use the properties of magnetic fields to measure the physical quantity. Examples of instruments that use magnetic principles include magnetic field sensors, Hall effect sensors, and magnetic flow meters.

5. **Thermal principle:** Measuring instruments based on thermal principles use the temperature-dependent properties of materials to measure the physical quantity. Examples of instruments that use thermal principles include thermocouples, resistance temperature detectors (RTDs), and infrared thermometers.

6. **Ultrasonic principle:** Measuring instruments based on ultrasonic principles use sound waves to measure the physical quantity. Examples of instruments that use ultrasonic principles include ultrasonic flow meters, ultrasonic thickness gauges, and ultrasonic distance meters.

In summary, measuring instruments operate based on various principles, and the selection of an appropriate instrument for a particular application depends on the nature of the quantity being measured, the accuracy required, and the operating conditions.

6.9 Moving Coil Instruments

Moving coil instruments are a type of electromechanical instrument used for measuring electrical quantities such as voltage, current, and frequency. They are commonly used in electrical and electronics applications due to their high accuracy, reliability, and sensitivity. Here's a detailed explanation of moving coil

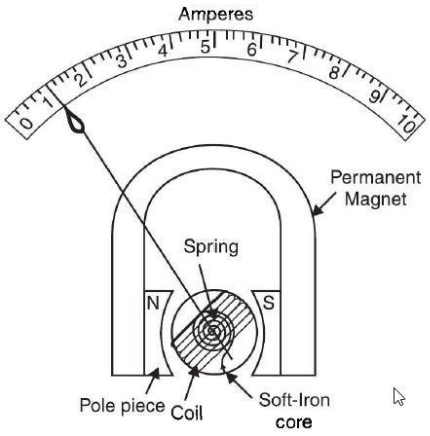
instruments:

Principle of Operation: Moving coil instruments work on the principle of electromagnetic induction. The instrument consists of a permanent magnet and a coil of wire that is free to rotate in the magnetic field. The coil is connected to a pointer or a scale to indicate the measured quantity.

When an electrical current flows through the coil, it generates a magnetic field that interacts with the permanent magnet, causing the coil to rotate. The amount of rotation depends on the strength of the magnetic field and the current flowing through the coil. As the coil rotates, the pointer attached to the coil indicates the measured quantity on a calibrated scale.

Types of Moving Coil Instruments: There are two types of moving coil instruments - Permanent magnet moving coil (PMMC) and Dynamometer type moving coil (D'Arsonval) instruments.

1. **Permanent Magnet Moving Coil (PMMC) instruments:** PMMC instruments are used for measuring DC voltages and currents. They are designed to operate with a permanent magnet and a stationary coil. When a current flows through the coil, it generates a magnetic field that interacts with the permanent magnet, causing the coil to rotate. The amount of rotation is proportional to the strength of the magnetic field and the current flowing through the coil. A calibrated scale is attached to the moving coil to indicate the measured quantity.



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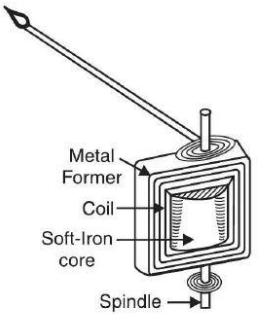
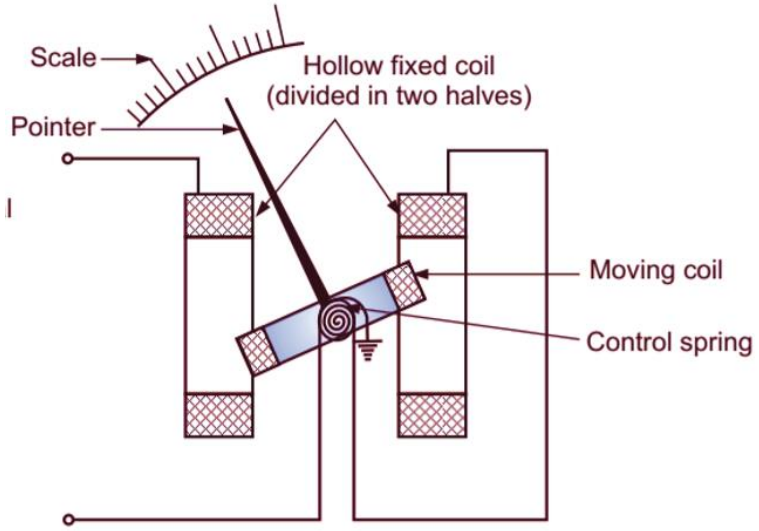


(*ii*)

2. **Dynamometer type Moving Coil (D'Arsonval) instruments:** Dynamometer type moving coil instruments are used for measuring AC and DC quantities. They are designed to operate with a fixed magnet and a movable coil. The coil is suspended between two springs and is free to rotate in the magnetic field. The springs provide the restoring torque to bring the coil back to its original position after it is deflected.



When a current flows through the coil, it generates a magnetic field that interacts with the fixed magnet, causing the coil to rotate. The amount of rotation is proportional to the strength of the magnetic field and the current flowing through the coil. The deflection is indicated on a calibrated scale attached to the coil.

Advantages of Moving Coil Instruments:

1. High accuracy and sensitivity.
2. Suitable for measuring DC and AC quantities.
3. Long operating life due to the absence of moving parts.
4. Low power consumption.

Limitations of Moving Coil Instruments:

1. Expensive compared to other types of instruments.
2. Limited dynamic range.
3. Susceptible to magnetic interference.
4. Not suitable for measuring high-frequency signals.

In summary, moving coil instruments are electromechanical devices used for measuring electrical quantities. They operate on the principle of electromagnetic induction and are available in different types depending on the application. They offer high accuracy and sensitivity, but are more expensive and have a limited dynamic range compared to other types of instruments.

6.10 Moving Iron Instruments

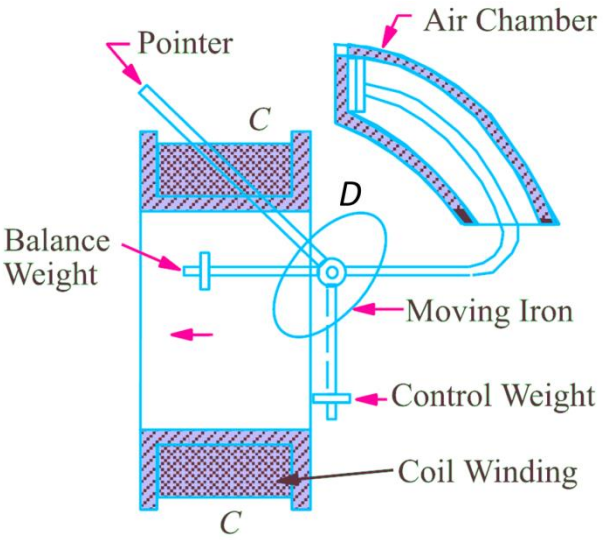
Moving iron instruments are a type of electromechanical instrument used for measuring AC and DC currents and voltages. They are commonly used in electrical and electronics applications due to their low cost, ruggedness, and wide dynamic range. Here's a detailed explanation of moving iron instruments:

Principle of Operation: Moving iron instruments work on the principle of attraction between magnetic fields. The instrument consists of a fixed iron core and a movable iron vane that is free to rotate in the magnetic field. The vane is connected to a pointer or a scale to indicate the measured quantity.

When a current flows through the coil, it generates a magnetic field that interacts with the iron vane, causing it to rotate. The amount of rotation depends on the strength of the magnetic field and the current flowing through the coil. As the vane rotates, the pointer attached to it indicates the measured quantity on a calibrated scale.

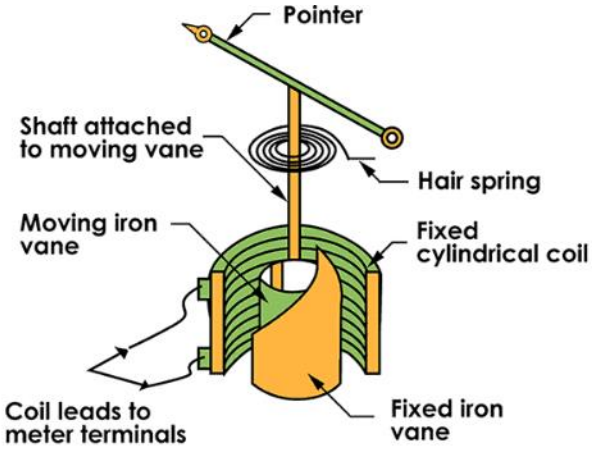
Types of Moving Iron Instruments: There are two types of moving iron instruments - Attraction type and Repulsion type.

1. **Attraction Type:** Attraction type moving iron instruments are used for measuring AC and DC currents and voltages. They are designed to operate with a fixed magnet and a movable iron vane. The vane is attracted towards the magnet due to the magnetic field produced by the current flowing through the coil. The amount of attraction is proportional to the strength of the magnetic field and the current flowing through the coil. A calibrated scale is attached to the vane to indicate the measured quantity.



2. **Repulsion Type:** Repulsion type moving iron instruments are used for measuring AC and DC currents and voltages. They are designed to operate with two fixed magnets and a movable iron vane. The vane is repelled by the

magnetic fields produced by the magnets due to the current flowing through the coil. The amount of repulsion is proportional to the strength of the magnetic field and the current flowing through the coil. A calibrated scale is attached to the vane to indicate the measured quantity.



Advantages of Moving Iron Instruments:

1. Low cost compared to other types of instruments.
2. Wide dynamic range.
3. Ruggedness and durability.
4. Suitable for measuring AC and DC quantities.

Limitations of Moving Iron Instruments:

1. Low accuracy and sensitivity compared to other types of instruments.
2. Non-linear scale.
3. Susceptible to magnetic interference.
4. Limited frequency response.

In summary, moving iron instruments are electromechanical devices used for measuring AC and DC quantities. They operate on the principle of attraction and repulsion between magnetic fields and are available in different types depending on the application. They offer a wide dynamic range and are relatively inexpensive, but have lower accuracy and sensitivity compared to other types of

instruments.

6.11 Principle of Energy Meter

An Energy meter is an instrument used for measuring the amount of electrical energy consumed by a consumer. It measures the electrical energy consumed by a consumer over a given period, usually a month or a billing cycle, and provides the data to the utility company for billing purposes.

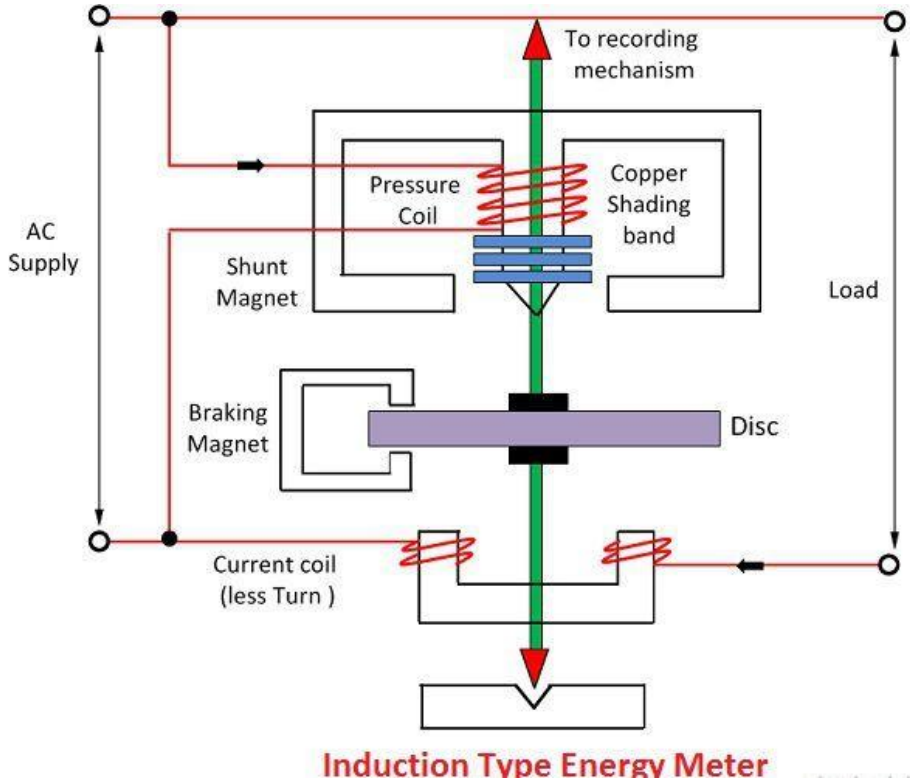
Energy meters are the basic part to measure the power consumption. It is used everywhere, no matter how big or small consumption it is. It is also known as watt-hour meter. Here we discuss the construction and working principle of induction type energy meter.

To understand the structure of watt-hour meter, we must understand the four essential components of the meter. These components are as follows:

1. Driving system
2. Moving system
3. Braking system
4. Registering system

Driving System

The components of this system are two silicon steel laminated electromagnets. The upper electromagnet is called shunt magnet and it carries a voltage coil consisting of many turns of thin wire. The lower electromagnet is called series magnet and it carries the two current coils consisting of a few turns of thick wire. Current coils are connected in series with the circuit and load current passes through it. Whereas voltage coil is connected to the supply mains and produce a high ratio of inductance to resistance. There is copper bands in the lower part of shunt magnet which provides frictional compensation so that the phase angle between shunt magnet flux and the supply voltage is exactly 90^{o}.



Induction Type Energy Meter

Moving System

As you can see in the figure, there is a thin aluminum disk placed in the gap between the two electromagnets and mounted on a vertical shaft. The eddy currents are induced in the aluminum disk when it cuts the flux produced by both the magnets. As a result of interference of eddy currents and two magnetic fields constitute a deflecting torque in the disk. As you start consuming power the disk slowly starts rotating and the several rotation of the disk displays the power consumption, in the particular interval of time. Normally it is measured in kilowatt-hours.

Braking System

The main part of this system is a permanent magnet called brake magnet. It is located near the disk so that eddy currents are induced in it due to movement of rotating disk through the magnetic field. This eddy current reacts with the flux

and exerts a braking torque which opposes the motion of the disk. The speed of the disk can be controlled by changing flux.

Registering System

As its name suggest, it registers the number of rotation of the disk which is proportional to the energy consumed directly in kilowatt-hour. There is a disk spindle which is driven by a gear on the disk shaft and indicates the number of times the disk has turned.

Working Principle of Energy Meter

The working of single phase induction type **energy meters** are based on two main fundamentals:

1. Rotation of aluminum disk.
2. Arrangement of counting and displaying the amount of energy consumed.

Rotation of an Aluminum Disk

The rotation of metallic disk is operated by two coils. Both the coils are arranged in such way that one coil produces a magnetic field in proportion to voltage and the other coil creates a magnetic field proportion to current. The field produced by voltage coil is delayed by 90^{o} so that eddy current is induced in the disk. The force exerted on the disk by the two fields is proportional to the product of the immediate current and voltage in the coils.

As a result of it, a light weight aluminum disk rotates in an air gap. But there is a need to stop a disk when there is no power supply. A permanent magnet works as a brake which opposes the rotation of the disk and balances the speed of rotation with respect to power consumption.

Arrangement of Counting and Displaying the Energy Consumed

In this system, the rotation of the floating disk has been counted and then displayed on the meter window. The aluminum disk is connected to a spindle which has a gear. This gear drives the register and the revolution of the disk has been counted and displayed on the register which has series of dials and each dial represent a single digit. There is a small display window in the front of the meter which displays the reading of energy consumed with the help of dials. There is a copper shading ring at the central limb of the shunt magnet. To make the phase angle between flux produced by shunt magnet and supply voltage about 900, small adjustments in the place of the ring is required.

Chapter 7
Sensors and Transducers

Sensors – Solenoids - Pneumatic Controls with Electrical Actuator - Piezoelectric - Hall Effect - Photo Sensors - Strain Gauge – LVDT - Differential Pressure Transducer - Optical and Digital Transducers - Smart Sensors - Thermal Imagers

7.1 Introduction

Sensors and transducers are devices that are used to measure or detect physical quantities or signals and convert them into electrical or mechanical signals that can be processed by electronic systems. They are widely used in a variety of applications, such as in industrial automation, medical devices, automotive systems, and consumer electronics.

A sensor is a device that converts a physical quantity or signal into an electrical signal. It measures a physical quantity, such as temperature, pressure, light, sound, or motion, and produces a corresponding electrical output signal that is proportional to the input signal. The most common types of sensors include temperature sensors, pressure sensors, optical sensors, magnetic sensors, and accelerometers.

A transducer, on the other hand, is a device that converts a physical quantity or signal into another physical quantity or signal. It can convert a mechanical signal, such as force or displacement, into an electrical signal, or vice versa. The

most common types of transducers include strain gauges, piezoelectric transducers, LVDTs (linear variable differential transformers), and thermocouples.

Sensors and transducers are often used together to create a complete sensing and measurement system. For example, a pressure transducer may be used to measure the pressure of a gas or fluid, and a temperature sensor may be used to measure the temperature of the fluid. The output signals from the two sensors can be combined to provide a more complete picture of the system being measured.

There are many factors to consider when selecting a sensor or transducer for a particular application, such as the range of the input signal, the accuracy and resolution required, the operating temperature range, the power consumption, and the size and cost of the device. It is important to choose the right device for the job to ensure accurate and reliable measurement results.

In summary, sensors and transducers are essential components in many electronic systems, and they play a critical role in measuring and detecting physical quantities or signals. They come in a wide range of types and configurations, each with their own strengths and weaknesses, and careful consideration must be given to selecting the right device for a particular application.

7.2 Sensors

A sensor is a device that detects or measures physical input or changes in the environment and converts it into an electrical signal that can be analyzed or processed by a computer or electronic system. The electrical signal can then be used to provide information about the physical input or to trigger a response from the system. Sensors are used in many applications, from measuring

temperature in a home thermostat to detecting the presence of obstacles in an autonomous vehicle.

There are many types of sensors available, and each has its own set of characteristics that make it suited for specific applications. Some common types of sensors include:

1. **Temperature sensors:** These sensors measure changes in temperature and convert them into an electrical signal. There are several types of temperature sensors, including thermocouples, which use two different metals to generate a voltage proportional to the temperature difference between them, and RTDs (resistance temperature detectors), which measure the change in resistance of a metal wire as the temperature changes
   .
2. **Pressure sensors:** These sensors measure the pressure of gases or liquids and convert it into an electrical signal. Examples of pressure sensors include piezoresistive sensors, which measure changes in resistance as pressure is applied, and capacitive sensors, which measure changes in capacitance as pressure is applied.

3. **Proximity sensors:** These sensors detect the presence of objects without physical contact. Some examples of proximity sensors include infrared sensors, which emit infrared light and measure the amount of light that is reflected back, and ultrasonic sensors, which emit high-frequency sound waves and measure the time it takes for the waves to bounce back.

4. **Motion sensors:** These sensors detect motion or movement and convert it into an electrical signal. Accelerometers, for example, measure changes in acceleration or vibration, while gyroscopes measure changes in orientation or angular velocity.

5. **Light sensors:** These sensors detect the presence and intensity of light and convert it into an electrical signal. Examples of light sensors include photodiodes, which generate a current when exposed to light, and photoresistors, which change resistance when exposed to light.

6. **Humidity sensors:** These sensors measure the amount of moisture in the air and convert it into an electrical signal. Examples of humidity sensors include capacitive sensors, which measure changes in capacitance as humidity changes, and resistive sensors, which change resistance as humidity changes.

7. **Gas sensors:** These sensors detect the presence of various gases and convert it into an electrical signal. Examples of gas sensors include electrochemical sensors, which generate a voltage proportional to the concentration of a gas, and catalytic sensors, which detect changes in the heat of a chemical reaction caused by the presence of a gas.

8. **Flow sensors:** These sensors measure the flow rate of liquids or gases and convert it into an electrical signal. Examples of flow sensors include thermal flow sensors, which measure changes in the temperature of a fluid as it flows past a sensor, and magnetic flow sensors, which measure the voltage generated by the movement of a conductive fluid through a magnetic field.

9. **Position sensors:** These sensors measure the position or displacement of objects and convert it into an electrical signal. Examples of position sensors include linear variable differential transformers (LVDTs), which measure changes in the position of a magnetic core, and potentiometers, which measure changes in resistance as a component is moved.

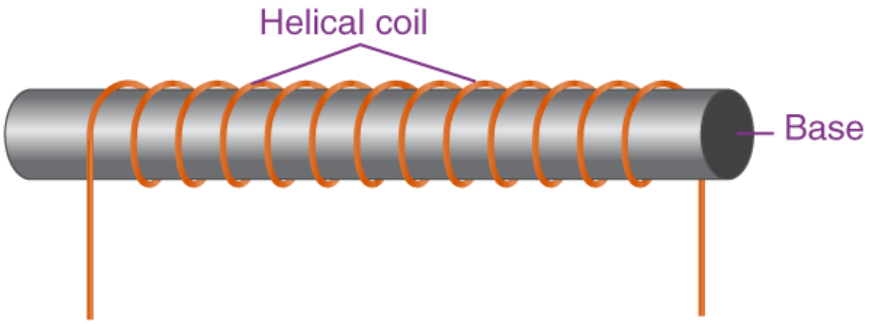
Sensors are essential components in many electronic systems, and careful consideration must be given to selecting the right sensor for a particular

application. Factors to consider when selecting a sensor include the range of the input signal, the accuracy and resolution required, the operating environment, and the cost of the sensor. In addition, it is important to consider the output signal of the sensor and how it will be processed by the electronic system.

Overall, sensors play a critical role in many modern technologies, from healthcare to transportation to manufacturing.

7.3 Solenoids

The solenoid is a type of electromagnet, the purpose of which is to generate a controlled magnetic field through a coil wound into a tightly packed helix. The solenoid is as shown in the figure below. The solenoid is a coil of wire, and the plunger is made of soft iron. The magnetic field is formed around the coil when an electric current passes through it and draws the plunger in. We can say that the solenoid is responsible for converting electrical energy into mechanical work.



Solenoids were the results of the development of an efficient and greater strength offering magnets. In the year 1823, a French Physicist and a mathematician, Andre-Marie Ampere coined the term solenoid to designate a helical coil.

Note: Electromagnet with the fixed core is not considered a solenoid.

Working of Solenoids

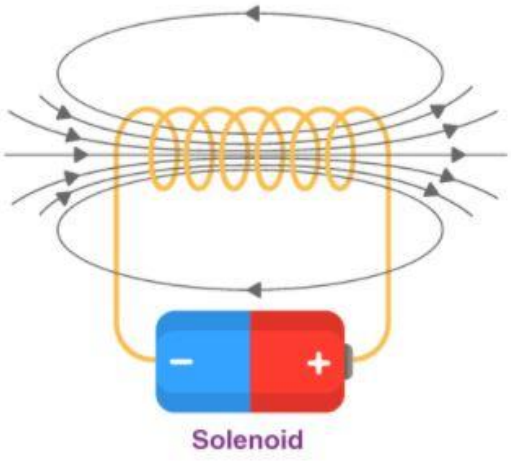
After understanding the definition of solenoid and its parts, let us learn how

solenoids work. Solenoid works on the principle of electromagnetism. When the electric current passes through the coil, the magnetic field is generated. When a metal core is placed inside the coil, the magnetic lines of flux are concentrated on the core. This increases the induction of the coil as compared to the air core. This concept is known as electromagnetic induction.

As we know, coils are made of numerous turns of copper wire wound tightly around it. A strong magnetic flux is developed when the current passes through the wire. The concentration of flux is high on the core, while some of the flux appears at the ends of the coil and outside the coil too. By increasing the flow of electric current or by increasing the density of the turns, the magnetic strength of the solenoid can be increased.

The housing is made of iron or steel. Housing is surrounded by the magnetic field created due to the coil. The plunger lets the mechanical force do work. Solenoids too feature positive and negative poles, through which an object can be attracted or repelled.

Consider a solenoid whose length is more than the radius. Enamelled and insulated wire is wrapped with a wire in the form of a helix with a small gap between the turns. The amount of vector force provided by each turn, and the total magnetic field created by the solenoid are equal to that formed by a circular loop. This gives the total magnetic field of the solenoid. The lines of magnetic fields produced within a finite solenoid are as shown below.



The field at any point beyond the solenoid is very thin. The field inside the solenoid is parallel to its axis at all times. The magnetic force produced by a solenoid can be defined using the Law of the Ampere:

$$F = \mu_0 nI$$

Where n is the number of turns of the wire per unit length, I is the current flowing through the wire, and the direction is given using the right-hand thumb rule.

Types of Solenoids

Different types of solenoids are as follows:

- AC-Laminated Solenoid
- DC-C Frame Solenoid
- DC-D Frame Solenoid
- Linear Solenoid
- Rotary Solenoid

Let us know about each type of solenoid.

AC-Laminated Solenoid

The AC-laminated solenoid is known for the amount of force that can occur in its first stroke. The AC-laminated solenoid features a metal core and a coil of

wire. The core of the solenoid is made with a laminated metal to reduce the stray current. AC-laminated solenoids are capable of using more strokes than DC laminated solenoids. This type of solenoid produces a clean buzzing sound when they operate.

DC C-Frame Solenoid

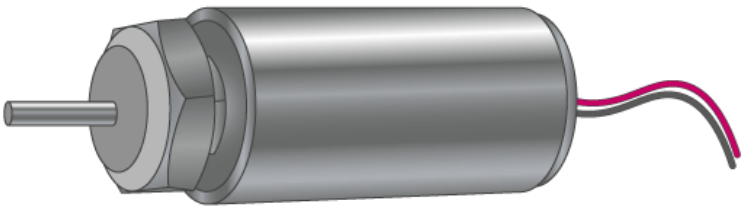
The DC C-Frame solenoid has one frame in C-shape covered around the coil. The DC C-frame solenoid is said to be DC configuration and can be used in equipment designed for AC power.

DC-D Frame Solenoid

DC-D frame solenoid is a two-piece frame covering the coil. It has a controlled stroke operation and can be used with AC power too.

Linear Solenoid

Linear solenoid features a coil of wire wrapped around movable metalcore. It aids in applying pulling or pushing force to a mechanical device. The linear solenoid is used in starting devices. This mechanism aids in completing a circuit and letting current flow through.



Linear solenoid

Rotary Solenoid

The rotary solenoid is used in the automatic control process. This solenoid also features a coil and a core, but it has a different operation.

Applications of Solenoid

1. They are used in construction, agricultural vehicles, speciality vehicles, and industrial equipment.
2. Linear solenoids are used in highly secured door mechanisms
3. They are used in starter motors of bikes and cars.
4. It is used in gaming machines, scanners, printers, circuit breakers, and photographic shutters.

7.4 Pneumatic Controls with Electrical Actuator

Pneumatic controls with electrical actuators are a type of control system that uses compressed air to actuate a valve or other mechanical device, with the electrical actuator providing the control signal to the pneumatic system. This type of system is commonly used in industrial and commercial applications, such as HVAC systems, process control, and manufacturing automation.

The basic components of a pneumatic control system with an electrical actuator include the following:

1. **Control signal source:** This is typically an electrical controller or programmable logic controller (PLC) that generates the control signal to actuate the electrical actuator.

2. **Electrical actuator:** This is an electrically-powered device that converts the electrical control signal into mechanical motion. The most common types of electrical actuators used in pneumatic control systems include solenoids and motors.

3. **Pneumatic valve or actuator:** This is the mechanical device that is actuated by the compressed air. Depending on the application, the valve or actuator can be a simple on/off device, or it can be a more complex proportional control device that allows for precise control of flow or pressure.

4. **Pneumatic supply:** This is the source of compressed air that is used to actuate the valve or actuator. The compressed air can be supplied from a central air compressor system or from a local air compressor unit.

In a typical pneumatic control system with an electrical actuator, the control signal is sent from the controller or PLC to the electrical actuator. The electrical actuator then converts this signal into mechanical motion, which is used to control the flow of compressed air to the pneumatic valve or actuator. This, in turn, causes the valve or actuator to move and perform the desired action, such as opening or closing a valve, or controlling the speed or direction of a pneumatic actuator.

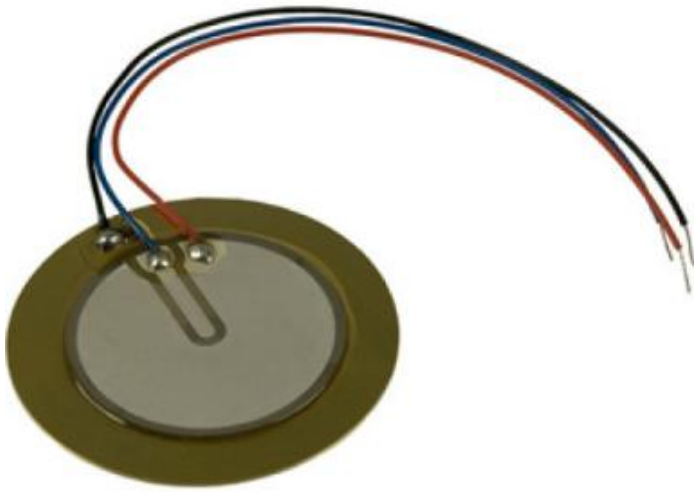
One of the key advantages of pneumatic controls with electrical actuators is their reliability and durability. Because the system is powered by compressed air, it is less susceptible to electrical or electronic failures, making it ideal for use in harsh or hazardous environments. Additionally, the use of electrical actuators allows for precise control of the pneumatic system, making it a popular choice in applications where accurate control of flow or pressure is critical.

In summary, pneumatic controls with electrical actuators are a robust and

reliable type of control system that combines the advantages of compressed air with the precision and control of electrical actuators. This type of system is widely used in a variety of industrial and commercial applications, where it provides reliable and accurate control of mechanical devices.

7.5 Piezoelectric

A piezoelectric transducer is used as a basis of the origin of the piezoelectric influence. The piezoelectric influence is a complex phenomenon and consists of electronics concepts and many fields of classical physics including elasticity, mechanics, optics, thermodynamics, acoustics, electrostatics, the strength of materials, wave propagation, fluid dynamics, circuit theories, crystallography, etc.

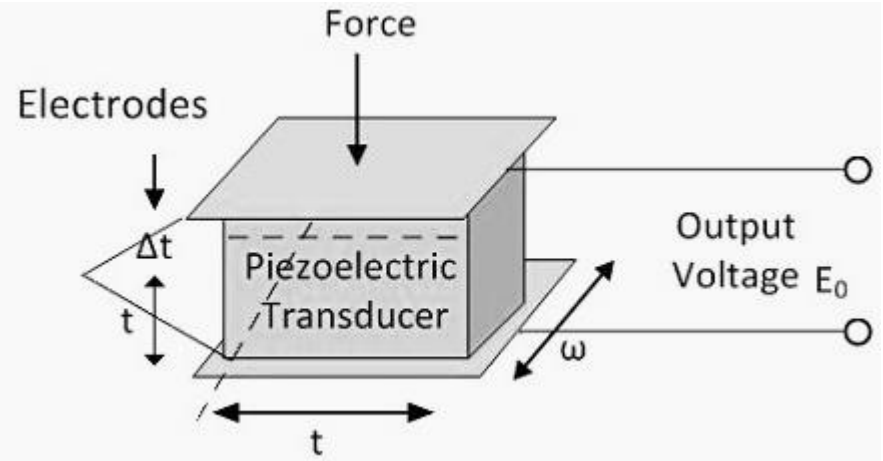


Schematic of Piezoelectric Transducer

Nowadays, we should measure physical variations such as mechanical pressure applied on metal, temperature ranges modifications, and stress levels in our different situations. We require an instrument that could measure these unfamiliar variations for all these applications in units and calibrations which are known to us. One of these instruments which are most beneficial for us is the Transducer. The transducer is an electrical instrument that can transform any kind of physical quantity to comparable electrical quantities such as electrical current or voltage. The purpose of this post is to explain piezoelectric

transducers from various types of the transducer.

The word piezoelectric is obtained from the Greek word piezen, which means to press or squeeze. The piezoelectric influence explains that when mechanical pressure or forces are applied to quartz crystals, generate electrical loads on the surface of quartz crystals. It is identified by Pierre and Jacques Curie. The level of load generated will be influenced by the rate of variation of mechanical force applied to it. i.e. the higher the force, the higher the electrical quantities.



Piezoelectric Transducer principle

One of the special features of the piezoelectric influence is that it is able to be turned the other way around or reversible. It means that when voltage is applied to Piezoelectric transducer, it changes the dimension along with a particular plane, i.e., quartz crystal setup is located into an electric field, it will modify quartz crystal by an amount influenced by the strength of the electrical effect. If the same setup is set into an electric field and the direction of the field turn, the modification will be inversed.

The piezoelectric transducer is too sensitive. Therefore, it operates as a sensor and is utilized in an accelerometer according to its perfect frequency of reaction. The piezoelectric influence is utilized in many applications that contain the generation and identification of sound, electronic frequency production. It operates as an ignition origin for cigarette lighter and employed in force,

pressure, microphone, sonar, and displacement measurement.

Piezoelectric Transducers Types

There are different types of them classified by key factors such as piezoelectric crystal material. Some of the limitations that set the nature of the crystal for the application are mentioned as the following:

- The angle at which the wafer is sliced from natural quartz crystal
- Dimension of the plate
- Thickness of the plate
- Method of mounting

Ceramic Piezoelectric Transducers

Based on the capability to generate a ceramic transducer in multiple shapes and sizes, ceramic transducers can be simply modified to a lot of diversities of industrial applications. As a result, they permit for a perfect organization to meet a customer's particular requirements. Nowadays, the most practical utilization of ceramic piezoelectric transducer manufacturing materials is the compositions of lead zirconate titanate, a solution that dates back to the 1960s. As ceramic transducer application has continued to develop, the utilization of piezo-polymers and composites has obtained acceptance generally.

Rochelle Salt Piezoelectric Transducers

Another material that operates appropriately in transducers is Rochelle salt, which is an artificial synthetic crystal. From many materials that indicate the piezoelectric influence, Rochelle salt generates the highest output of any other material identified thus far.

Nevertheless, it does have its problems, which can reduce its performance in certain applications. These synthetic crystals cannot use in contact with any humidity. They also cannot be utilized at a temperature above 240 degrees

Celsius.

If you want to use sensitivity for voltage peak output, synthetic crystals can perform more reliable than natural crystals.

Piezoelectric Transducers based on Operation

A piezoelectric transducer can be classified into sonic, ultrasonic, and mega-sonic transducers based on the working frequency. In all of these classifications, the function and design of transducer change obviously. The sonic transducer operates at an audible frequency level which is less than 20 kHz. Buzzer and unimorph transducer are the main examples of sonic piezoelectric transducers. The ultrasonic transducers normally operate at between 20 to 200 kHz. Finally, the mega sonic transducers operate at the frequency level of MHz.

The principle of a Piezoelectric Transducer

Based on how a piezoelectric material is sliced, three main principles of operation can be introduced for Transducers. They are transverse, longitudinal, and shear.

Transverse effect

When pressure is applied to the main axis ‘y’ then it produces loads and charges along the ‘x’ direction, at an angle of 90° from the line of pressure. The charge is based on the geometrical dimensions of the piezoelectric material.

Longitudinal effect

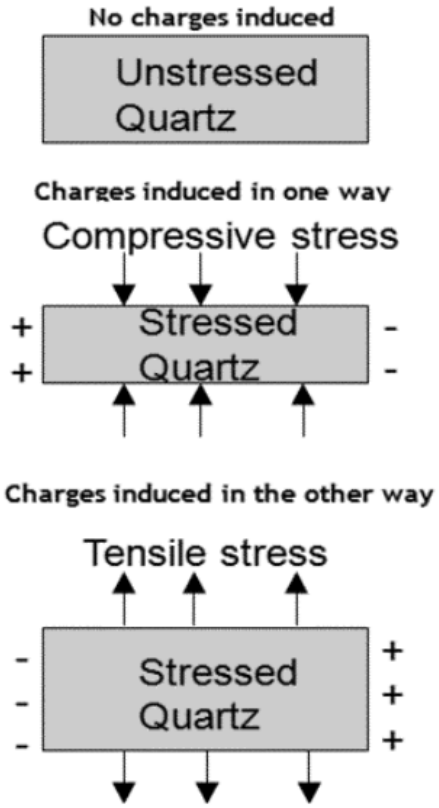
The amount of load generated is based on the applied force. Unlike the transverse effect, this load is independent of the shape and size of the piezoelectric component.

Shear effect

The load generated is based on the applied forces and they are independent of the size and shape of the element like the Longitudinal effect.

Piezoelectric Transducer Working

Piezoelectric Transducer working is based on the principle of piezoelectricity. The root of piezoelectric material, usual quartz, is covered with a thin layer of conducting material like silver. But at first, we must explain the role of quartz crystals in Transducers. A piezoelectric transducer contains quartz crystal which is constructed from silicon and oxygen ordered in the crystalline system (SiO_2). Typically, the main cell (basic repeating unit) of all crystal is uniform and symmetric but not in piezoelectric quartz crystals. Piezoelectric crystals are electrically unbiased and neutral.



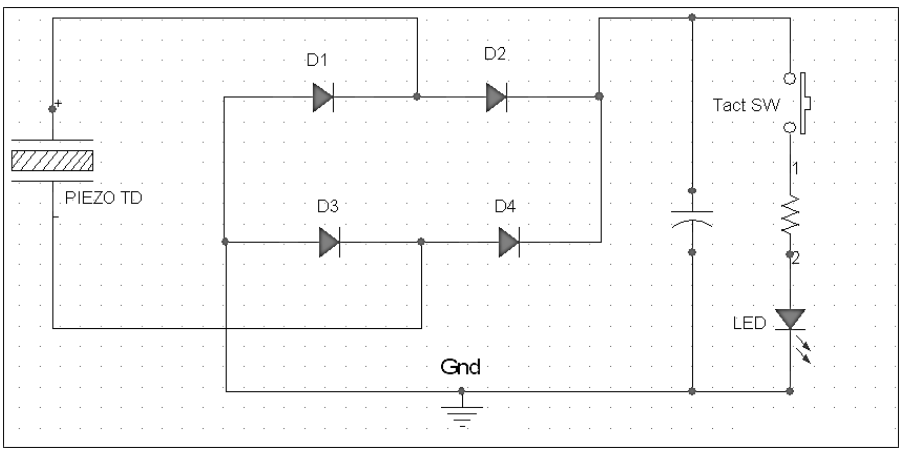
Piezoelectric Transducers Working

The atoms inside the crystals may not be regularly ordered but their electrical loads are moderate means positive charges neutralize negative ones. The quartz crystal has the specific feature of producing electrical polarity when mechanical force and stress applied to it along a particular surface. Generally, there are two kinds of stress. One is compressive and the other one is tensile.

When there is unstressed quartz, no loads induce on it. In the condition of compressive stress, positive loads are induced on one part and negative loads are induced on the other side. The crystal size becomes longer and thinner according to compressive stress. In the condition of tensile stress, loads are induced in the reverse direction as compared to compressive force and quartz crystal becomes fatter and shorter. If you want to see how this Transducer works more precisely, visit here.

Circuit Diagram of Piezoelectric Transducers

Piezoelectric transducers are contained as an important part of electric and electronic circuits to utilize their electromechanical characteristics in both reverse and direct applications. Thus, it is essential to provide an electric model including the piezoelectric components in electric circuits. This will considerably simplify the analysis of the circuit and the comprehension of its working. The operation of a fundamental transducer can be described by the below figure.



Piezoelectric Transducer Circuit Diagram

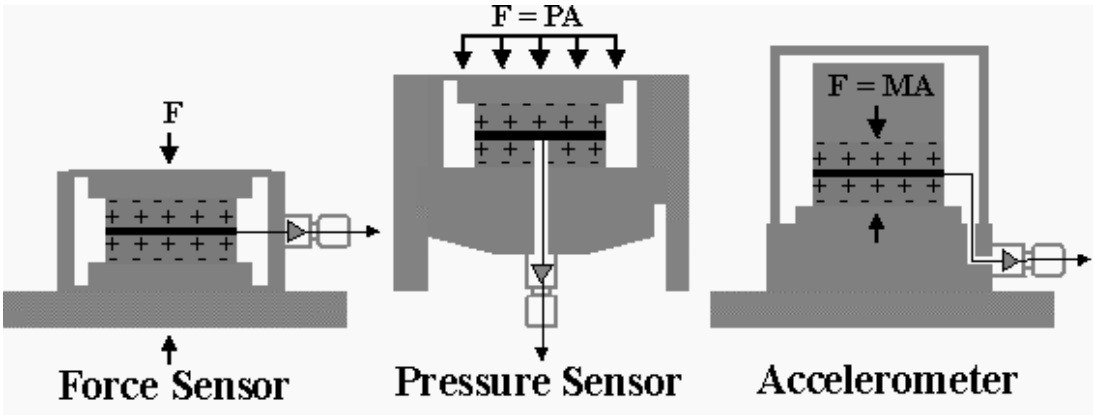
Quartz crystal covered with silver is utilized as a sensor to produce a voltage when force is applied to it. A load amplifier is employed to measure the generated charge without loss. The resistance used in the circuit is very high. The capacitance of the lead wire that attaches the transducer and piezoelectric

sensor influences the calibration. So, the load amplifier is generally located next to the sensor.

As a result, when mechanical force is applied in a transducer, a comparable electric voltage is produced which is amplified utilizing load amplifier and employed for calibration of applied force.

Piezoelectric Transducer Applications

The applications of these transducers are too different. Piezoelectric transducers can be utilized for applications that employ electric power for environmental, industrial, and personal usages.



Piezoelectric Transducer Applications

By utilizing piezoelectric materials, transducers can be employed in a variety of applications, including:

- Air Piezoelectric transducers are regularly utilized in automobile, proximity, and level sensors. They are used in medical diagnostics, infertility treatments, and in ultrasonic imaging for medical applications.
- They are usually employed in residential products like motion and object identifiers, home security alarms, and pest deterrents. Producers apply them to popular electronic instruments such as games, toys, and remote-control units. You can also find them in electric toothbrushes, inkjet printers, and buzzers.
- As piezoelectric materials cannot measure static variations, these are

basically employed for measuring plate roughness, in accelerometers, and as a vibration detector. For instance, they are utilized in seismographs to evaluate the vibrations in rockets, or in strain gauges to estimate the vibrations of applied force and stress. They are also utilized for researches on blast waves and high-speed shock waves.

- Piezoelectric transducers are also used by automotive producers to evaluate detonations in engines. They are also employed in automobile seat belts to lock in the reaction to a rapid reduction.
- The sound pressure is transformed into an electric signal in microphones and this signal is eventually increased to generate a louder sound. In electric lighter in kitchens, when the pressure is applied to the piezoelectric transducer, it produces an electric signal which eventually causes the flash to fire up.
- They are also employed in restaurants or airports. In this condition, when a person steps near the door, the door opens automatically using a Piezoelectric transducer. The concept utilized is that when a person is near the door, an electric effect is generated and the door opens automatically.

Advantages and Disadvantages of Piezoelectric Transducers

Piezoelectric transducers have various advantages mentioned as the following:

- These are active transducers. It means that they don't need external power and force for operation and are self-producing.
- The high-frequency reaction of these piezoelectric transducers makes them a perfect choice for different applications because some parameters in these applications change too quickly.
- They are easy to handle and utilize due to their small dimensions.

Nevertheless, Piezoelectric transducers have some disadvantages as the following.

- Environmental conditions like temperature variations can influence the

behavior of the piezoelectric transducers.

- They are not suitable for measurement in static applications. Piezoelectric Transducers can only measure dynamic pressure and are useless to measure static parameters.
- The output voltage of Piezoelectric Transducers is occasionally low in some applications. So, some external amplifiers must attach to their circuit.
- It is very hard to give the desired strength and shape to piezoelectric materials. Therefore, piezoelectric transducers always utilize in the same shape and design in different applications.

7.6 Hall Effect

The hall effect sensor is a type of magnetic sensor which can be used for detecting the strength and direction of a magnetic field produced from a permanent magnet or an electromagnet with its output varying in proportion to the strength of the magnetic field being detected.

Magnetic sensors are solid state devices that are becoming more and more popular because they can be used in many different types of application such as sensing position, velocity or directional movement.

They are also a popular choice of sensor for the electronics designer due to their non-contact wear free operation, their low maintenance, robust design and as sealed hall effect devices are immune to vibration, dust and water.

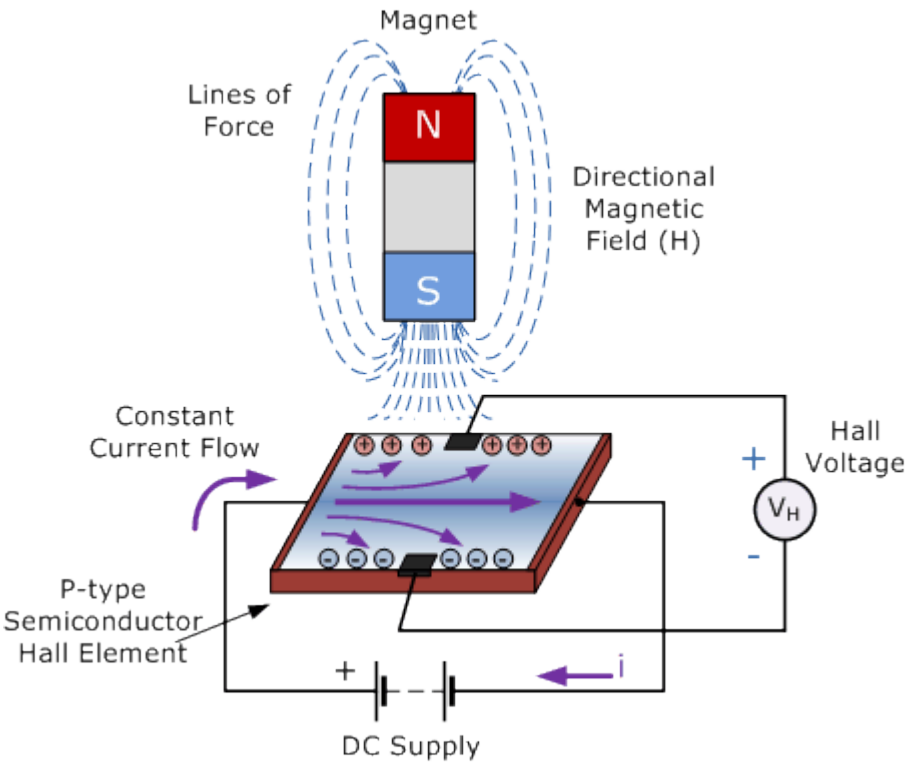
One of the main uses of magnetic sensors is in automotive systems for the sensing of position, distance and speed. For example, the angular position of the crank shaft for the firing angle of the spark plugs, the position of the car seats and seat belts for air-bag control or wheel speed detection for the anti-lock braking system, (ABS).

Magnetic sensors are designed to respond to a wide range of positive and negative magnetic fields in a variety of different applications and one type of magnet sensor whose output signal is a function of magnetic field density around it is called the Hall Effect Sensor.

Hall Effect Sensors are devices which are activated by an external magnetic field. We know that a magnetic field has two important characteristics flux density, (B) and polarity (North and South Poles).

The output signal from a Hall effect sensor is the function of magnetic field density around the device. When the magnetic flux density around the sensor exceeds a certain pre-set threshold, the sensor detects it and generates an output voltage called the **Hall Voltage, V_H**. Consider the diagram below.

Hall Effect Sensor Principles



Hall Effect Sensors consist basically of a thin piece of rectangular p-type semiconductor material such as gallium arsenide (GaAs), indium antimonide (InSb) or indium arsenide (InAs) passing a continuous current through itself.

When the device is placed within a magnetic field, the magnetic flux lines exert a force on the semiconductor material which deflects the charge carriers, electrons and holes, to either side of the semiconductor slab. This movement of charge carriers is a result of the magnetic force they experience passing through the semiconductor material.

As these electrons and holes move side wards a potential difference is produced between the two sides of the semiconductor material by the build-up of these charge carriers. Then the movement of electrons through the semiconductor material is affected by the presence of an external magnetic field which is at right angles to it and this effect is greater in a flat rectangular shaped material.

The effect of generating a measurable voltage by using a magnetic field is called the **Hall Effect** after Edwin Hall who discovered it back in the 1870's with the basic physical principle underlying the Hall effect being Lorentz force. To generate a potential difference across the device the magnetic flux lines must be perpendicular, (90^o) to the flow of current and be of the correct polarity, generally a south pole.

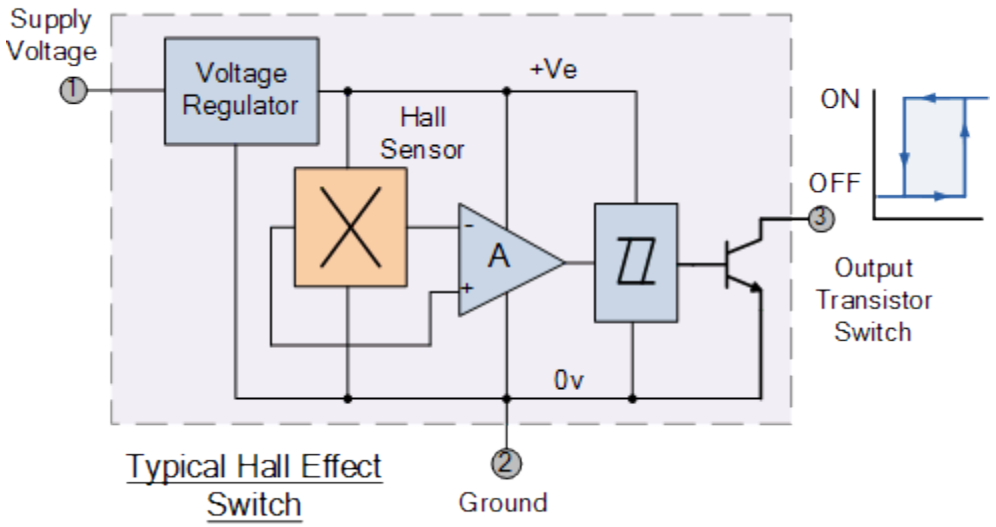
The Hall effect provides information regarding the type of magnetic pole and magnitude of the magnetic field. For example, a south pole would cause the device to produce a voltage output while a north pole would have no effect. Generally, Hall Effect sensors and switches are designed to be in the "OFF", (open circuit condition) when there is no magnetic field present. They only turn "ON", (closed circuit condition) when subjected to a magnetic field of sufficient strength and polarity.

Hall Effect Magnetic Sensor

The output voltage, called the Hall voltage, (V_H) of the basic Hall Element is directly proportional to the strength of the magnetic field passing through the semiconductor material (output ∝ H).

This output voltage can be quite small, only a few microvolts even when subjected to strong magnetic fields so most commercially available Hall effect devices are manufactured with built-in DC amplifiers, logic switching circuits and voltage regulators to improve the sensors sensitivity, hysteresis and output voltage.This also allows the Hall effect sensor to operate over a wider range of power supplies and magnetic field conditions.

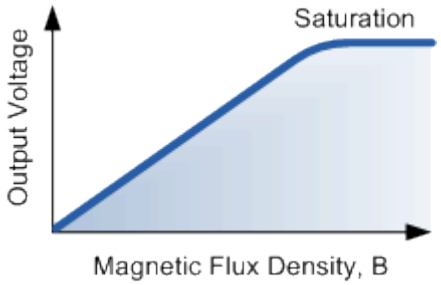
The Hall Effect Sensor



Hall Effect Sensors are available with either linear or digital outputs. The output signal for linear (analogue) sensors is taken directly from the output of the operational amplifier with the output voltage being directly proportional to the magnetic field passing through the Hall sensor. This output Hall voltage is given as:

$$V_H = R_H\left(\frac{I}{t} \times B\right)$$

- Where:
- V_H is the Hall Voltage in volts
- R_H is the Hall Effect co-efficient
- I is the current flow through the sensor in amps
- t is the thickness of the sensor in mm
- B is the Magnetic Flux density in Teslas



Linear or analogue sensors give a continuous voltage output that increases with a strong magnetic field and decreases with a weak magnetic field. In linear output Hall effect sensors, as the strength of the magnetic field increases the output signal from the amplifier will also increase until it begins to saturate by the limits imposed on it by the power supply. Any additional increase in the magnetic field will have no effect on the output but drive it more into saturation.

Digital output sensors on the other hand have a Schmitt-trigger with built in hysteresis connected to the op-amp. When the magnetic flux passing through the Hall sensor exceeds a pre-set value the output from the device switches quickly between its "OFF" condition to an "ON" condition without any type of contact bounce.

This built-in hysteresis eliminates any oscillation of the output signal as the sensor moves in and out of the magnetic field. Then digital output sensors have just two states, "ON" and "OFF".

There are two basic types of digital Hall effect sensor, **Bipolar** and **Unipolar**. Bipolar sensors require a positive magnetic field (south pole) to operate them and a negative field (north pole) to release them while unipolar sensors require

only a single magnetic south pole to both operate and release them as they move in and out of the magnetic field.

Most Hall effect devices can not directly switch large electrical loads as their output drive capabilities are very small around 10 to 20mA. For large current loads an open-collector (current sinking) NPN Transistor is added to the output.

This transistor operates in its saturated region as a NPN sink switch which shorts the output terminal to ground whenever the applied flux density is higher than that of the "ON" pre-set point.

The output switching transistor can be either an open emitter transistor, open collector transistor configuration or both providing a push-pull output type configuration that can sink enough current to directly drive many loads, including relays, motors, LEDs, and lamps.

Hall Effect Applications

There are many different applications for **Hall Effect Sensors** especially as proximity sensors. They can be used instead of optical and light sensors were the environmental conditions consist of water, vibration, dirt or oil such as in automotive applications. Hall effect devices can also be used for current sensing.

7.7 Photo Sensors

The photoelectric sensor is an electrical device that responds to a change in the intensity of the light falling upon it. Modern photoelectric sensors offer precise lens and intelligent electronics as a standard. Both components are integrated into robust housings made of resistant plastic or metal.

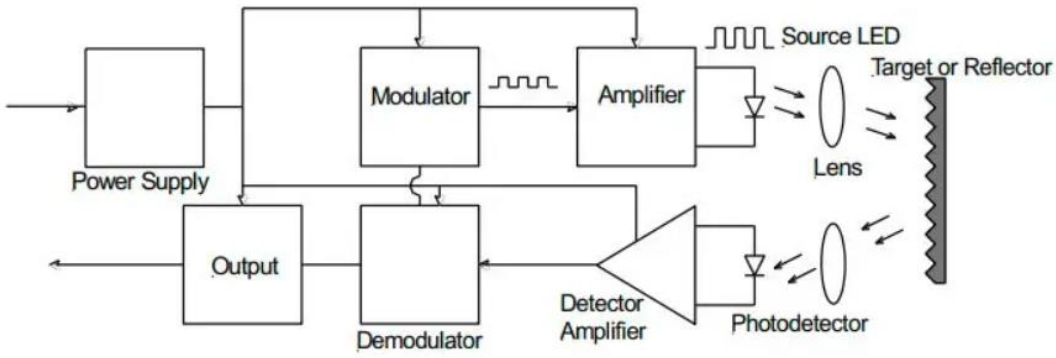
The photoelectric sensor has a long sensing distance, fast response time, and high resolution. It can be used to detect virtually any object without touching it.

Working

The function of a photoelectric sensor is to use light to detect the presence or absence of an object. A photoelectric sensor consists of the sensor, control unit, and output. The source is a light-emitting diode that emits a powerful beam of infrared or visible light. The detector is typically a photodiode that senses the presence or absence of light.

Basic components of a photosensor:

- Source LED
- Photodetector
- Lens (for source and detector)
- Power Circuit (modulator and demodulator)
- Amplifier
- Output Circuit



There are many different types of photoelectric sensor technologies. The most popular technologies are through-beam, reflective, diffuse, and background suppression.

Thru-beam sensing

A through-beam method consists of a transmitter and receiver mounted opposite each other. Each time an object interrupts the direct path between transmitter and receiver the electrical response of the receiver transistor or the receiver diode changes. This change can be used to detect the presence of an object using

electronics and can be signalled via an output stage.

Thru-beam detection generally provides the longest range and provides higher power at a shorter range to penetrate steam, dirt, or other contaminants between the source and the detector. The alignment of the source and detector must be accurate.

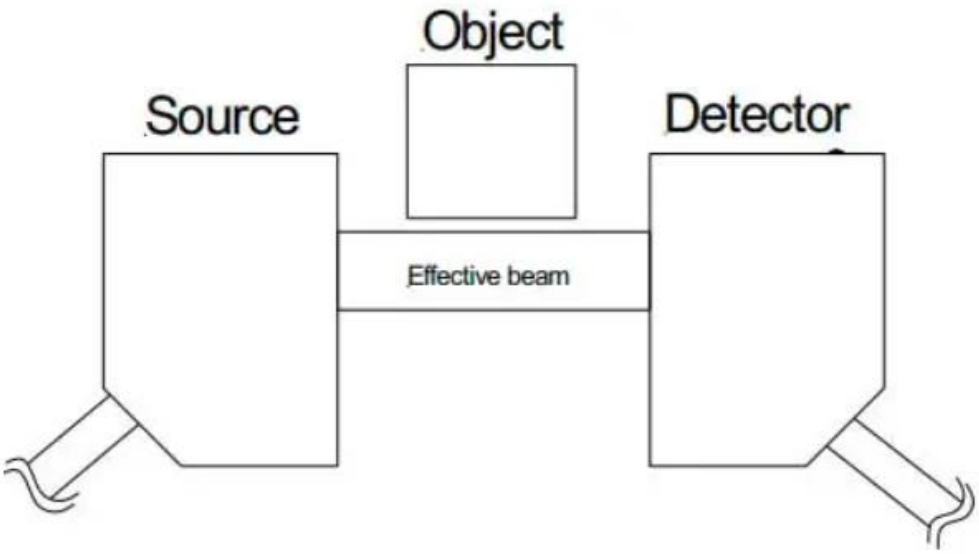
The effective beam area is that of the column of light that travels straight between the lenses. Because the light from sources is transmitted directly to a photodetector, thru-beam sensing offers the following advantages:

Advantages of thru beam sensing are:

- It has the longest range for sensing.
- It has the highest possible signal strength.
- It has the greatest light/dark contrast ratio.
- It has the best trip point repeatability.

Disadvantages of thru beam sensing are:

- It requires the wiring of the two components across the detection zone.
- It may be difficult to align the source and detector.
- If the object detected is smaller than the effective beam diameter, an aperture over the lens may be required.



Diffuse sensing

The diffuse sensing method requires that the source and detector are installed on the same side of the object to be detected and aimed at a point in front of the sensor. When an object passes in front of the source and detector, light from the source is reflected from the object's surface back to the detector, and the object is detected. The main strength of diffuse sensors is the detection of very small objects at close distances.The optimum range for the diffuse and reflex sensor is more significant than the maximum range. The optimum range is best shown by an excess gain chart.

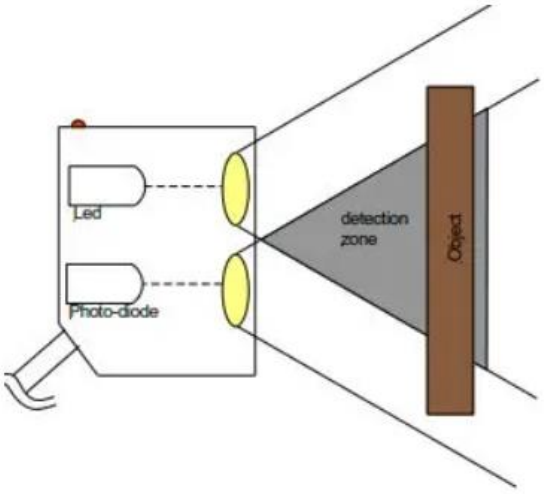
The detecting zone is controlled by the type, texture, and composition of the object.

Advantages of diffuse sensing:

- Installation and alignment are simple and involve wiring on one side.
- It can detect the difference in surface reflectivity.

Disadvantages of diffuse sensing:

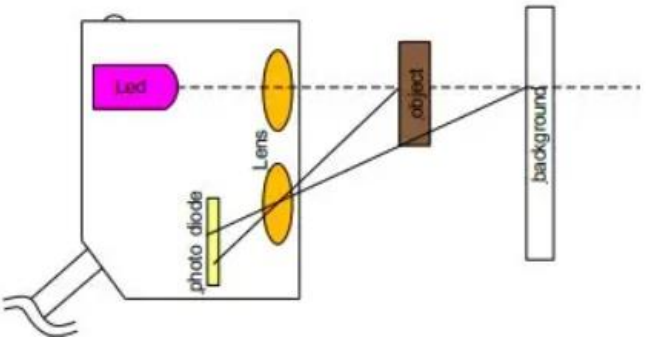
- It has a limited sensing range.
- The light/dark contrast sensing range depends on the target object's surface reflectivity.



Background suppression

Background suppression enables the diffuse sensor to have excess gain to a predetermined limit and insufficient excess gain beyond that range where it might pick up objects in motion and yield false detection. By using triangular ranging, sensor developers have created a sensor that emits light that reflects on the detector from two different target positions.

The signal received from the distant target is subtracted from the closer target, providing high excess gain for the closest target.



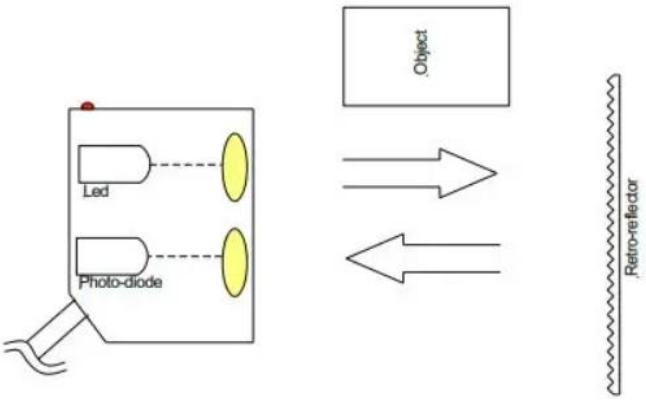
Reflective sensing

The reflective sensing method requires that the source and detector are installed on the same side of the object to be detected. The light beam is transmitted from the source to a retro-reflector that returns the light to the detector. When an

object breaks a reflected beam, the object is detected.

The reflective method is widely used because it is flexible and easy to install and provides the best cost-performance ratio of the three methods. The object to be detected must be less reflective than a retroreflector.

Since the light travels in two directions (hence twice the distance), reflex sensors will not sense as far as thru-beam sensors. However, reflex sensors offer a powerful sensing system that is easy to mount and does not require that electrical wire be run on both sides of the sensing area. The main limitation of these sensors is that a shiny surface on the target object can trigger false detection.



Below, you can see some advantages and disadvantages of each technology.

Through-beam: Most accurate, longest sensing range, very reliable / Must be installed at two points onthe system: emitter and receiver. Costly – must purchase both emitter and receiver.

Reflective: Cost less than through-beam, Only slightly less accurate than through-beam, Sensing range better than diffuse. Very reliable. / Must be installed at two points on the system: sensor and reflector. Slightly more costly than diffuse. Sensing range less than through-beam.

Diffuse: Only install at one point. Costs less than through-beam or reflective. / Less accurate than through-beam or reflective. More setup time is involved.

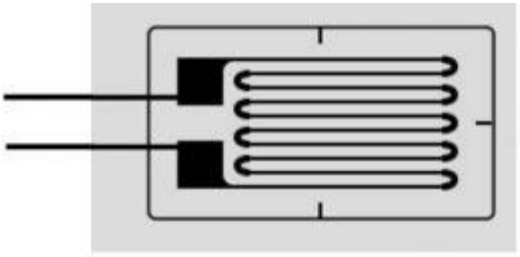
Background suppression: Effective with reflective backgrounds. / Cost more than diffuse, reflective, or through-beam. Most setup time required.

Photoelectric sensors have wide application areas in the industry:

- Detecting tab threads.
- Counting packages.
- Determining and detecting the orientation of the IC chip.
- Detecting jams on a conveyor.
- Detecting caps on bottles.
- Detecting components inside the metal can.
- Detecting items of varying heights.
- Controlling the height of a stack.
- Counting boxes anywhere on a conveyor.
- Verifying liquid in vials.
- Detecting labels with transparent backgrounds.
- Verifying screws are correctly seated.
- Detecting reflective objects.

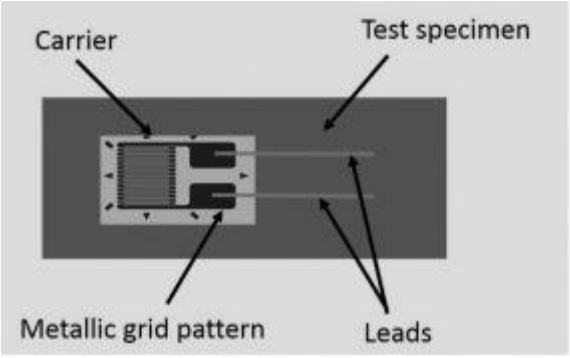
7.8 Strain Gauge

A strain gauge is one of the imperative devices used in the field of geotechnical engineering to measure strain on diverse structures. By applying an external force, there would be a change in resistance of a strain gauge.

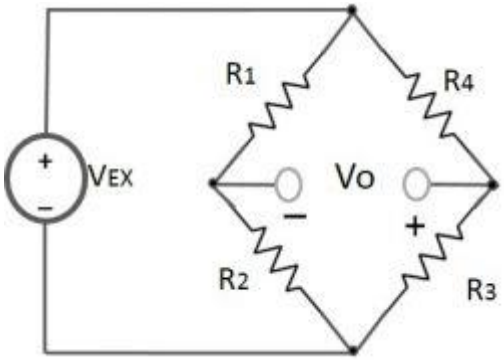


The basic construction of a gauge has an insulating flexible backing to support a metallic foil structure. This metallic coil is glued to a thin backing called a

carrier, and the entire setup is fixed to an object using a suitable adhesive. As the object is deformed due to force, pressure, weight, tension, etc., the electrical resistance of foil changes. A Wheatstone bridge measures the change in resistivity, which is related to strain through a quantity known as Gauge Factor.



The small changes in resistance of a gauge are measured using the concept of Wheatstone bridge. The figure below illustrates the general Wheatstone bridge, which has four resistive arms and an excitation voltage, V_{EX}.



Wheatstone bridge

The Wheatstone bridge has two parallel voltage divider circuits. R1 and R2 form a one voltage divider circuit, R3 and R4 form second voltage divider circuit. The output voltage VO is given by:

$$\mathbf{Vo=[R3/(R3+R4\ )-R2/(R1+2)]* V_{EX}}$$

If R1/R2 = R4/R3, then the output voltage is zero and the bridge is said to be a balanced bridge.

A small change in resistance leads to a nonzero output voltage. If 'R4' is

replaced with a strain gauge and any changes in the resistance of strain gauge will unbalance the bridge and produce nonzero voltage.

Gauge Factor of Strain Gauge

The gauge factor GF is given as**GF= (ΔR⁄RG)/∈**

Where,

'ΔR' is the change in resistance due to strain

'RG' is the resistance of the undeformed gauge

'ε' is the strain

The gauge factor of common metallic foils is around 2. The output sensor voltage SV of a Wheatstone bridge is given by,**SV=EV (GF.∈)/4**

Where EV is the bridge excitation voltage

Strain Gauge Working

The functioning of a strain gauge entirely depends on the electrical resistivity of an object/conductor. When an object gets stretched within its limits of elasticity and does not break or buckle permanently, it becomes thinner and longer, resulting in high electrical resistance. If an object is compressed and does not deform, but, broadens and shortens, results in decreased electrical resistance. The values obtained after measuring the electrical resistance of a gauge helps to understand the amount of stress-induced.

The excitation voltage is applied at the input terminals of a gauge network, while the output is read at the output terminals. Normally, these are connected to a load and are likely to remain stable for longer periods, sometimes decades. The glue used for gauges depends on the duration of a measurement system – cyanoacrylate glue is suitable for short term measurements and epoxy glue for long term measurements.

Strain Gauge Working Principle

As we know that the resistance is directly dependent on the length and cross-sectional area of a conductor, which is given by **R = L/A**

Where,

'R'= Resistance

'L' = Length

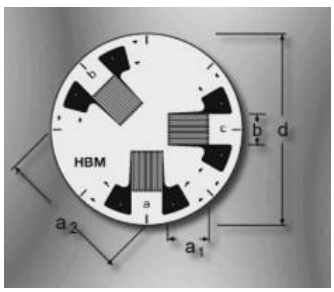
'A' = cross-sectional area

Clearly, the length of a conductor is altered with the change in size and shape of a conductor, eventually, altering the cross-sectional area and resistance.

Any normal gauge has a conductive strip that is long and thin, placed in a zig-zag fashion of parallel lines. The purpose of this zig-zag alignment is to elaborate on the small amount of stress that occurs between the parallel lines with much accuracy. Stress is defined as the resisting force of an object.

Strain Gauges Rosettes

Two or more gauges positioned closely in a rosette-like structure to measure the number of components to evaluate precise strain on the surface are known as strain gauge rosettes. The illustration is shown in the figure below.



Strain Gauge Load Cells

These load cells are most commonly found in industrial applications. It is highly precise and economical. Basically, a load cell consists of a metal body on which strain gauges are attached. For the metal body to be sturdy and less elastic, alloy

steel, aluminum, or stainless steel are employed to design.

When an external force is applied on a load cell, the load cell is slightly deformed, and if not overloaded, it returns to its original shape.

If the load cell deforms, the gauge changes in shape, causing the change in electrical resistance of gauge, which in turn measures voltage.

There are common types of strain gauge load cells, which include bending beam, pancake, single point shear beam load cell, double-ended shear beam, wire rope clamps, and so on.

Characteristics of Strain Gauges

The important characteristics of strain gauges are:

- These are appropriate for longer periods with certain precautions
- They provide precise values with a change in temperature and other factors
- These are easy to manufacture because of simple components
- They are easy to maintain and has a long operating life
- This is totally encapsulated to protect from damages like handling and installation

Applications of Strain Gauge

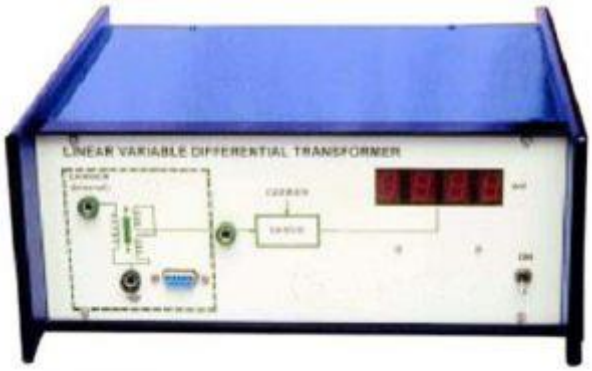
The exceptional features enable these gauges to be used in the field of geotechnical engineering to monitor structures like dams, tunnels, etc. constantly and to avoid accidents well in advance. Some of the applications of strain gauges include –

- Rail monitoring
- Cable bridges
- Aerospace
- Nuclear power plants

7.9 LVDT

The LVDT full form is “Linear Variable Differential Transformer” is LVDT. Generally, LVDT is a normal type of transducer. The main function of this is to convert the rectangular movement of an object to the equivalent electrical signal. LVDT is used to calculate displacement and works on the transformer principle.

The LVDT sensor diagram comprises a core as well as a coil assembly. Here, the core is protected by the thing whose location is being calculated, while the coil assembly is increased to a stationary structure. The coil assembly includes three wire-wound coils on the hollow shape. The inside coil is the major, which is energized by an AC source. The magnetic flux generated by the main is attached to the two minor coils, making an AC voltage in every coil.



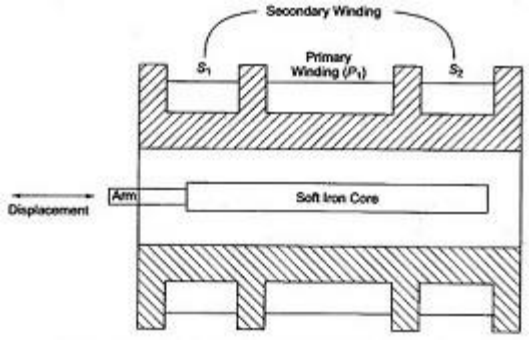
Linear Variable Differential Transformer

The main benefit of this transducer, when compared with other LVDT types, is toughness. As there is no material contact across the sensing component.

Because the machine depends on the combination of magnetic flux, this transducer can have an unlimited resolution. So the minimum fraction of progress can be noticed by an appropriate signal conditioning tool, and the transducer’s resolution is exclusively determined by the declaration of the DAS (data acquisition system).

Linear Variable Differential Transformer Construction

LVDT comprises a cylindrical former, which is bounded by one main winding in the hub of the former and the two minor LVDT windings are wound on the surfaces. The amount of twists in both the minor windings is equivalent, but they are reversed to each other like clockwise direction and anti-clockwise direction.

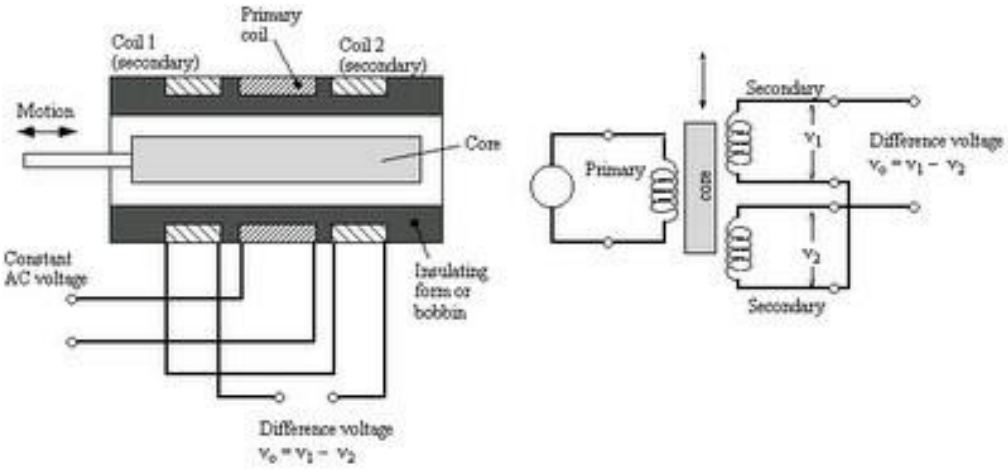


Linear Variable Differential Transformer Construction

For this reason, the o/p voltages will be the variation in voltages among the two minor coils. These two coils are denoted with S1 & S2. Esteem iron core is located in the middle of the cylindrical former. The excitation voltage of AC is 5-12V and the operating frequency is given by 50 to 400 HZ.

Working Principle of LVDT

The working principle of the linear variable differential transformer or LVDT working theory is mutual induction. The dislocation is nonelectrical energy that is changed into electrical energy. And, how the energy is altered is discussed in detail in the working of an LVDT.



LVDT Working Principle

Working of an LVDT

The working of the LVDT circuit diagram can be divided into three cases based on the position of the iron core in the insulated former.

- **In Case-1:** When the core of the LVDT is at the null location, then both the minor windings flux will equal, so the induced e.m.f is similar in the windings. So for no dislocation, the output value (e_{out}) is zero because both the e1 & e2 are equivalent. Thus, it illustrates that no dislocation took place.
- **In Case-2:** When the core of the LVDT is shifted up to the null point. In this case, the flux involving minor winding S1 is additional as contrasted to flux connecting with the S 2 winding. Due to this reason, e1 will be added as that of e2. Due to this e_{out} (output voltage) is positive.
- **In Case-3:** When the core of the LVDT is shifted down to the null point, Inthis case, the amount of e2 will be added as that of e1. Due to this e_{out} output voltage will be negative plus it illustrates the o/p to down on the location point.

What is the Output of LVDT?

The output of the measuring device like LVDT or linear variable differential transformer is a sine wave through amplitude that is proportional to off-center location & 0º otherwise 180º of phase based on the located side of the core.

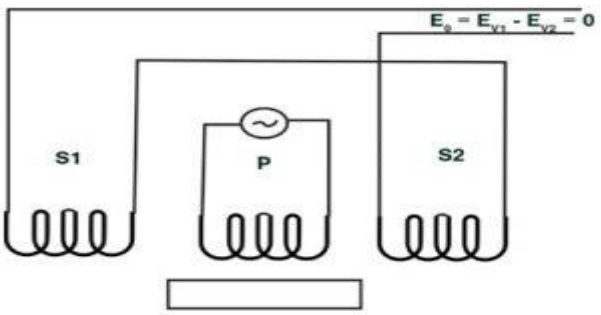
Here, full-wave rectification is used to demodulate the signal. The highest value of the engine out (EOUT) happens at the highest core displacement from the middle position. It is an amplitude function of the main side excitation voltage as well as the sensitivity factor of the specific type of LVDT. In general, it is quite considerable at RMS.

LVDT Characteristics

The characteristics of LVDT mainly discussed in three cases like null position, highest right position & highest left position.

Null Position

The working procedure of LVDT can be illustrated at a null axial place otherwise zero by the following figure. In this condition, the shaft can be located exactly at the center of S1and S2 windings. Here, these windings are secondary windings, which increase the generation of equivalent flux as well as induced voltage across the next terminal correspondingly. This location is also called a null position.



LVDT at Null Position

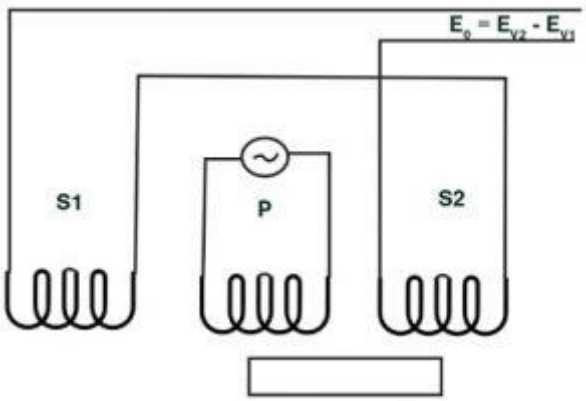
The output phase sequence as well as output magnitude differentiation with respect to input signals that derives displacement and movement of the core. The arrangement of the shaft at the neutral location or at the null mainly indicates that the induced voltages across secondary windings which are connected in series are equivalent & inversely proportional with respect to net o/p voltage.

EV1= EV2

$$Eo = EV1 – EV2 = 0\ V$$

Highest Right Position

In this case, the highest right position is shown in the below figure. Once the shaft is shifted in the right side direction, then a huge force can be generated across S2 winding, on the other hand, the minimum force can be produced across S1 winding.



LVDT at Right

Thus, the ‘E2’ (induced Voltage) is considerably superior to E1. The resultant differential voltages equations are shown below.

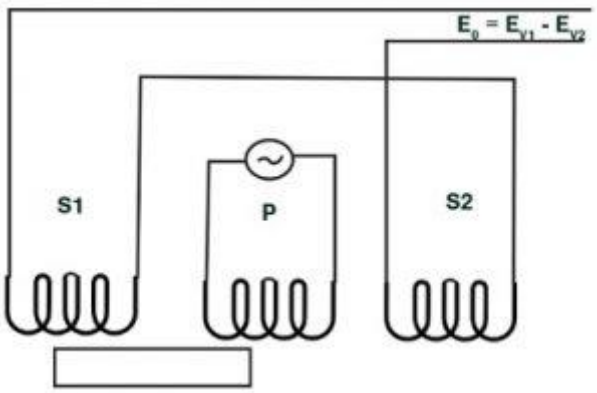
$$Eo = EV2 – EV1$$

Maximum Left Position

In the following figure, the shaft can be inclined more in the direction of the left side, then high flux can be generated across S1 winding & voltage can be induced across ‘E1’ when ‘E2’ is decreased. The equation for this is given below.

$$Eo = EV1 – EV2$$

The final LVDT output can be calculated in terms of frequency, current, or voltage. The designing of this circuit can also be done with microcontroller based circuits like PIC, Arduino, etc.

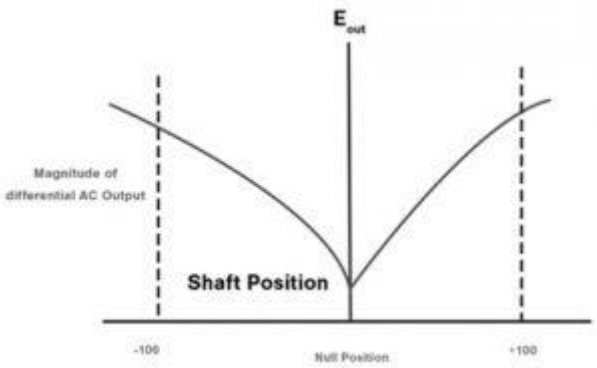


LVDT at Left

LVDT Graph

The LVDT graph diagrams are shown below which shows the variations in the shaft as well as their result in terms of the differential AC output's magnitude from a null point & output of direct current from electronics.

The utmost value of shaft displacement from the core location mainly depends on the sensitivity factor as well as the amplitude of the main excitation voltage. The shaft stays at the null position until a referenced main excitation voltage is specified to the main winding of the coil.



LVDT Shaft Variations

As shown in the figure, the DC o/p polarity or phase shift mainly defines the position of the shaft for the null point to represent the property like the o/p linearity of the module of LVDT.

Advantages and Disadvantages of LVDT

The LVDT advantages and disadvantages include the following.

- The measurement of the displacement range of LVDT is very high, and it ranges from 1.25 mm to -250 mm.
- The LVDT output is very high, and it doesn't require any extension. It owns high compassion which is normally about 40V/mm.
- When the core travels within a hollow former consequently there is no failure of displacement input while frictional loss, so it makes an LVDT a precise device.
- LVDT demonstrates a small hysteresis and thus repetition is exceptional in all situations
- The power consumption of the LVDT is very low about 1W as evaluated by another type of transducers.
- LVDT changes the linear dislocation into an electrical voltage which is simple to progress.
- LVDT is responsive to move away from magnetic fields, thus it constantly needs a system to keep them from drift magnetic fields.
- It is accomplished that LVDTs are more beneficial as contrasted than any kind of inductive transducer.
- LVDT gets damaged by temperature as well as vibrations.
- This transformer needs large displacements to get significant differential output
- These are responsive to stray magnetic fields
- The receiving instrument should be chosen to work on AC signals otherwise a demodulator n/w should be used if a dc o/p is necessary
- The limited dynamic response is there mechanically through the mass of the core & electrically through the applied voltage.

Linear Variable Differential Transformer Applications

The applications of the LVDT transducer mainly include where dislocations to

be calculated that are ranging from a division of mm to only some cms.

- The LVDT sensor works as the main transducer, and that changes dislocation to an electrical signal straight.
- This transducer can also work as a secondary transducer.
- LVDT is used to measure the weight, force, and also pressure
- In ATMs for Dollar bill thickness
- Used for soil moisture testing
- In machines for making PILLS
- Robotic cleaner
- It is used in medical devices for brain probing
- Some of these transducers are used to calculate the pressure and load
- LVDT's are mostly used in industries as well as servomechanisms.
- Other applications like power turbines, hydraulics, automation, aircraft, and satellites

7.10 Differential Pressure Transducer

A pressure transducer converts pressure into an electrical output signal. The electrical signal can be digital or analog and is used by other devices such as controllers, alarms, and other closed-loop systems. Pressure transducers are used widely in a range of residential and commercial applications like HVAC, pumps, vehicles, aircraft, etc. where pressure measurement is required. They are also referred to as pressure sensors or pressure transmitters.

Pressure transducer working principle

A pressure transducer consists of a pressure-sensitive element, such as a diaphragm, with a constant area. The fluid pressure causes the diaphragm to deflect. The pressure transducer also consists of a transduction element. This transduction element converts the deflection sensed by the diaphragm into an electrical output signal. This signal will increase or decrease proportionally to the pressure change. Therefore, device calibration is critical to ensure that the

pressure is within the range of the specifications.

Pressure transducers require a power supply to produce electrical signals. The signal is commonly 4-20 mA or 0-10 V DC. Some systems may also use a combination of AC and DC power. The 4-20 mA signal is a widely used standard in the industry. It uses a 2-wire configuration while DC voltage output uses a 3-wire configuration. The 4-20 mA signal can be used over long distances and is less sensitive to interference than a DC signal.

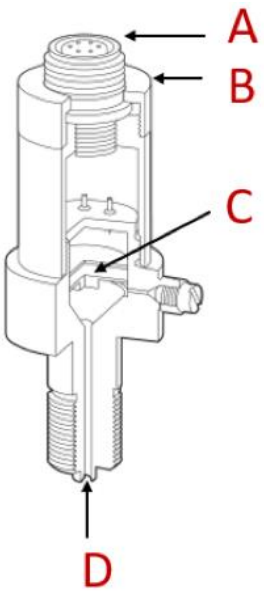
A pressure transducer should not be confused with a pressure switch. A pressure switch is a device that operates an electrical contact when a preset fluid pressure is reached.

Types of pressure transducers

There are different types of pressure transducers based on their measurement technology. The main types are outlined below:

Strain gauge pressure transducer

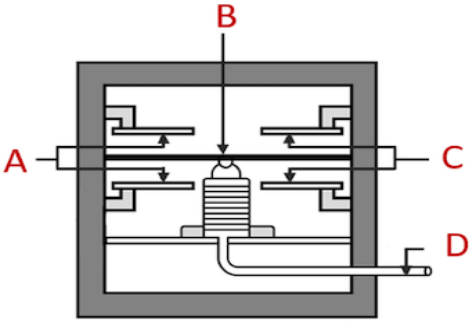
These transducers are suitable to measure extraordinarily high and low pressures, as well as differential pressure. Differential pressure is the difference in pressure between any two given points. The transducer contains a sensing element, a diaphragm. Any deformation of the diaphragm will cause a change in the resistance of the strain gauges. Typically, 4 gauges are used in a Wheatstone bridge to maximize the sensitivity of the transducer. This resistance change is converted into a usable output signal.



Strain gauge pressure transducer components: connector (A), housing (B), strain gauge (C), & pressure inlet (D)

Capacitance pressure transducer

Capacitance pressure transducers measure pressure by detecting the changes in electrical capacitance due to the movement of the diaphragm. It has two capacitor plates, a diaphragm, and an electrode fixed to an unpressurized surface. These plates are at a certain distance from each other, and the change in pressure will widen or narrow the gap between these plates. This change in capacitance is converted into a usable signal.

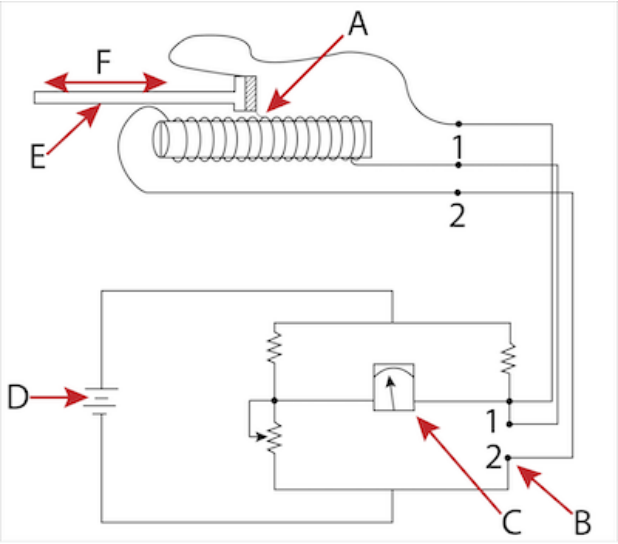


Capacitance pressure transducer components: insulated standoffs (A), diaphragm (B), capacitor plates (C), & pressure port (D)

Depending upon the application, this transducer can measure either absolute, gauge, or differential pressure.

Potentiometric pressure transducer

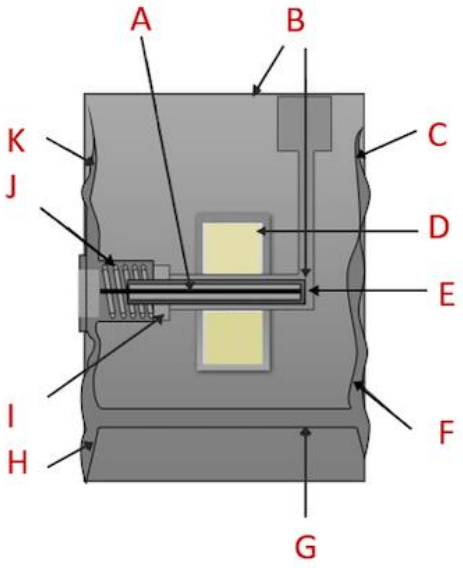
This type of transducer consists of a precision potentiometer. The potentiometer consists of a wiper connected to the pressure-sensitive element, such as a diaphragm. The deflection on this element changes the position of the wiper. The resistance value changes between the wiper and one end of the potentiometer. This value is the measure of the pressure applied.



Potentiometric pressure transducer components: wiper (A), resistance-measuring bridge circuit (B), measurement proportional to pressure (C), bridge power supply (D), movable arm of pressure element (E), & displacement (F)

Resonant wire pressure transducer

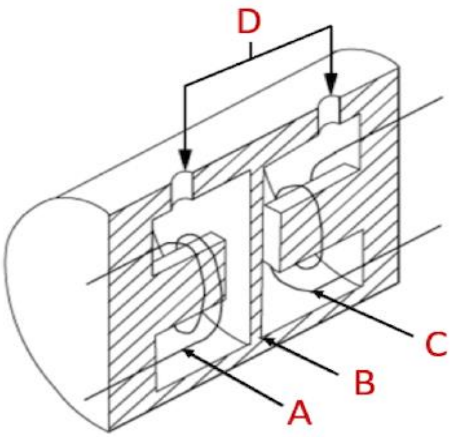
Resonant wire pressure transducers have a vibrating wire located in a diaphragm. The electronic oscillator keeps the wire vibrating. As the pressure changes in the diaphragm, it affects the tension of the wire and changes the resonant frequency. This frequency can be sensed by digital counter circuits and converted into an electrical signal.



Resonant wire pressure transducer components: resonant wire (A), to oscillator circuit (B), high-side backup plate (C), magnet (D), metal tube (E), high-pressure diaphragm (F), fluid transfer port (G), low-pressure diaphragm (H), electrical insulator (I), preload spring (J), & low-side backup plate (K)

Inductive pressure transducer

Inductive pressure transducers operate using the principle of electromagnetic induction. The transducer has a diaphragm connected to a ferromagnetic core.

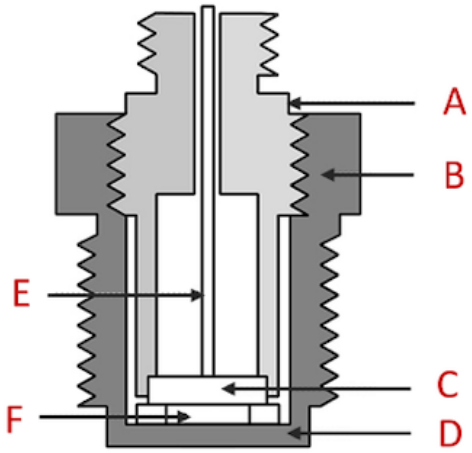


Inductive pressure transducer components: coil (A, C), diaphragm (*B),* ***&pressure (D)***

The slight deflection of the diaphragm causes linear movement in the ferromagnetic core, which induces a current. The movement of the core due to the change of pressure varies the induced current. This change in current is converted into a usable signal.

Piezoelectric pressure transducer

The piezoelectric pressure transducers use quartz crystal or ceramic material to generate an electric charge when there is applied pressure. This electric charge, measured as a voltage, is proportional to the change in pressure. This transducer is very sensitive and extremely fast in response.



Sectional view of piezoelectric pressure transducer components: nut(A), housing (B), crystal (C), diaphragm (D), lead wire (E), & disc (F)

Applications

Pressure transducers are used in a wide range of residential and commercial applications that require pressure measurement. Therefore, depending on the media there are air pressure transducers, liquid pressure transducers, and gas pressure transducers. Some typical electronic pressure transducer applications include:

- Monitoring the brake and fuel pressure in vehicles.
- Monitoring liquid levels in a HVAC system.

- Sensing the liquid level for well and pump stations.
- Altitude sensing for aircraft and satellites.
- Monitoring liquid and gas levels on various medical devices.

7.11 Optical and Digital Transducers

Optical and digital transducers are two types of sensors that are used to measure physical or environmental variables, such as temperature, pressure, or light intensity. They are widely used in a variety of applications, including manufacturing, automation, and environmental monitoring.

Optical transducers rely on the properties of light to measure a physical variable. They use a light source, such as a laser or LED, to generate a beam of light that is directed at the material or environment being measured. The light interacts with the material or environment in some way, such as being absorbed, reflected, or refracted, and this interaction is used to determine the physical variable of interest. For example, in a temperature measurement system, an optical transducer may use the amount of light absorbed by a material to determine the material's temperature.

Digital transducers, on the other hand, convert a physical variable into a digital signal that can be processed by a computer or other digital device. They use a sensing element, such as a resistor or strain gauge, to convert the physical variable into an electrical signal. This electrical signal is then converted into a digital signal using an analog-to-digital converter (ADC). The digital signal can then be processed and analyzed by a computer or other digital device.

Both optical and digital transducers have advantages and disadvantages, and their selection depends on the specific application requirements. Optical transducers typically have higher accuracy and resolution than digital transducers, but they can be more complex and expensive. Digital transducers are often more robust and easier to use, but they may not have the same level of

accuracy or resolution as optical transducers.

Some common examples of optical transducers include:

1. **Fiber optic sensors:** These sensors use optical fibers to measure physical variables such as temperature, strain, or pressure. The fibers can be designed to interact with the material being measured in various ways, such as bending or twisting in response to strain, or changing their refractive index in response to temperature.
2. **Photodetectors:** These sensors measure the intensity of light, and are commonly used in applications such as light detection and ranging (LIDAR), photovoltaic cells, and optical communication.
3. **Spectrometers:** These sensors measure the spectrum of light emitted or absorbed by a material, and can be used for applications such as chemical analysis, environmental monitoring, and astronomy.

Some common examples of digital transducers include:

1. **Thermistors:** These sensors measure temperature by changing their electrical resistance in response to temperature changes.
2. **Pressure sensors:** These sensors measure pressure by converting the pressure into a change in electrical resistance, capacitance, or inductance.
3. **Strain gauges:** These sensors measure mechanical strain by converting the strain into a change in electrical resistance or capacitance.

Overall, both optical and digital transducers are important sensors in many applications, and their selection depends on the specific requirements of the application.

7.12 Smart Sensors

A smart sensor is a device that uses a transducer to gather particular data from a physical environment to perform a predefined & programmed function on the particular type of gathered data then it transmits the data through a networked

connection.

The **features of the smart sensor** are; self-identification, digital sensor data, smart calibration & compensation, multi-sensing capacity, sensor communication for configuration of remote & remote monitoring, etc.

Smart Sensors

Smart Sensor Working Principle

Smart sensors work by capturing data from physical environments & changing their physical properties like speed, temperature, pressure, mass, or presence of humans into calculable electrical signals. These sensors include a Digital Motion Processor (DMP). Here a DMP is one type of microprocessor that allows the sensor to perform onboard processing of the smart sensor data like filtering noise otherwise performing different kinds of signal conditioning.

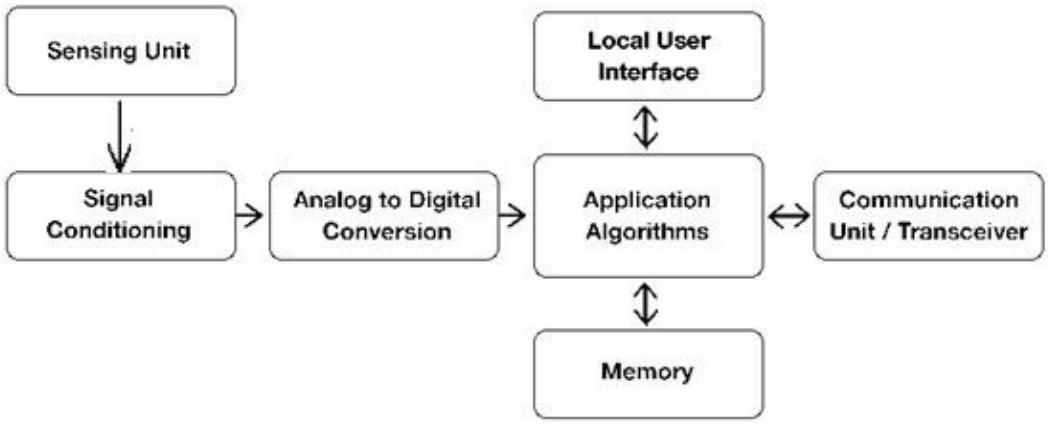
These sensors have 4 main functions measurement, configuration, verification & communication.

- Measurements are simply taken through detecting physical signals & changing them into electrical signals. So this will help in monitoring and measuring things like temperature, traffic, & industrial applications.
- Configuration function is a significant feature as it allows the smart sensor to detect position otherwise installation errors
- The verification function has different uses like nonstop supervision of sensor behavior, using a set of supervisory circuits or equipment executed within the sensor.

- Lastly, the communication feature allows the sensor to converse to the main microcontroller/ microprocessor.

Smart Sensor Block Diagram

The block diagram of the smart sensor is shown below. This block diagram includes different blocks like sensing unit, signal conditioning, analog to digital conversion, application algorithms, local user interface, memory, and communication unit or transceiver.



Smart Sensor Block Diagram

Sensing Unit

This unit detects the changes in physical parameters & generates electrical signals equivalent to it. Signal

Conditioning Unit

The signal conditioning unit controls the signal to meet the necessities of next-level operations without losing data.

Analog to Digital Converter

ADC converts the signal from analog to digital format & sends it to the microprocessor.

Local User Interface

The local user interface or LUI is a panel-mounted device used to allow building operators to monitor & control system equipment.

Application Algorithm

The signals from smart sensors reach here & process the received data based on the application programs previously loaded here & generate output signals.

Memory

It is used to store media for saving received & processed data.

Communication Unit

The output signals from the application algorithm or microprocessor are transmitted to the main station through the communication unit. This unit also gets command requirements from the key station to execute specific tasks.

Types of Smart Sensor

There are different types of smart sensor available in the market which is explained below.

Level Sensors

A level sensor is one type of device used to monitor measure & maintain liquid levels. Whenever the level of liquid is sensed, this sensor changes the data into an electric signal.

Level Sensors

Level sensors are classified into two types point level & continuous level. A point level sensor is used to specify whether a liquid has achieved an exact point within a container whereas continuous level type sensors are used to provide precise measurements for liquid level. These sensors are mainly used in different industries like automotive, manufacturing, and also in household applications.

Temperature Sensors

Temperature sensors are used to measure temperatures like liquid temperature, air temperature, or solid matter temperature. These sensors are available in different types which use different principles to measure the temperature like RTDs, NTC thermistors, thermopiles & thermocouples. These sensors are mainly used in medical devices, computers, automobiles, cooking appliances & other types of machinery.

Temperature Sensor

Pressure Sensors

A pressure sensor is a transducer that changes the mechanical pressure input into an electrical output signal. There are different types of pressure sensors available based on capacity, size, sensing technology, measurement method &output requirements. These sensors play a key role in monitoring pipelines & give an alert to overseers if there are any leaks otherwise irregularities so that they can repair or maintain pipelines.

Pressure Sensor

Infrared Sensors

An infrared sensor is an electronic device used to emit light to detect some object in the surroundings and measures the object's heat & detects the motion. Generally, all the objects will emit some form of thermal radiation within the IR spectrum which is invisible but the IR sensor can sense these radiations.

Infrared Sensor

IR sensor includes a transmitter like an IR LED and receiver as an IR photodiode. For infrared transmission, three types of media are used vacuum, atmosphere & optical fibers. These sensors are used in night vision devices, radiation thermometers, IR tracking, IR imaging, etc.

Proximity Sensors

A smart sensor like a proximity sensor is used to notice the existence of objects in its surrounding area without contacting them. These sensors are frequently used in collision avoidance systems & collision warnings. This sensor uses light, sound, IR radiation otherwise electromagnetic fields to notice an object.

Proximity Sensor

These sensors are applicable in consumer robotics, industrial applications and also utilized in vehicles to detect the physical contact of other vehicles & also for parking-assist functions

Air Quality Detection Sensors

Air quality detection sensors are electronic devices that are used to detect & monitor the air pollution within the air in the nearby area. So, these sensors efficiently work for indoor & outdoor purposes. Air quality sensors are capable of checking the CO2 concentrations through VOC (volatile organic compounds) that have methane & ammonia as gases.

Air Quality Detection Sensor

Motion Sensors

Motion sensors are electronic devices, used to detect movement inside and surroundings of your home and give an alert. For instance, this sensor can activate the lights once it detects you while entering into a room otherwise, they can give an alert once an intruder is trying to enter your home. These types of sensors are mainly used in homes, security systems, paper towel dispensers, phones, virtual reality systems & game consoles.

Motion Sensor

Smart Plant Sensors

Plant sensors are advanced gardening sensors used to provide the data to the user from stem surface, leaf to root probes to feed the plants. They explain to us what nourishment and care are required for the plant.

Plant Sensor

This sensor is very simple to use by placing it into the soil of the plant pot beside the potted plant. After that, it monitors the level of moisture, light intensity, the temperature automatically to maintain the plant properly. The current plant sensors give an alert through smartphones to keep checking your plant's condition remotely and take appropriate action.

Smart Climate Sensors

Smart climate sensors are used to gather the data of barometric pressure, temperature & humidity that assist in evaluating the exact weather conditions & calculate as well.

Climate Sensor

These sensors will assist you in setting your plan accordingly because these sensors are connected through your Smartphone to send alerts throughout the frequent changes within the weather. These sensors are essential for gardening and are connected to smart irrigation systems.

Difference between Normal Sensor & Smart Sensor

The difference between a normal sensor and a smart sensor includes the following.

Sensor	Smart Sensor
A sensor is a device used to detect the physical changing & chemical environment.	The part of a sensor is known as a smart sensor that is used for the computer.
A sensor doesn't include a DMP or digital motion processor.	A smart sensor includes a DMP or Digital Motion Processor.
The normal sensor includes three components like sensor element, packaging & connections, and also signals processing hardware.	Smart sensors include different components like amplifiers, transducers, analog filters, excitation control, and compensation sensors.
The different types of normal sensors are pressure, position, temperature, vibration, force, humidity & fluid property.	The different types of smart sensors are electric current, level, humidity, pressure, proximity, temperature, heat, flow, etc.
Normal sensor output cannot be used directly because we should convert it into a usable format.	The output of the smart sensor is ready to use.
Normal sensors are not expensive because they contain fewer components.	Smart sensors are expensive as compared to normal sensors.

Advantages

The **advantages of the smart sensor** include the following.

- These are small in size
- These sensors are very easy to use, design & maintain
- The performance level is higher
- Speed of communication & reliability is higher due to the direct conversion with the processor.
- These sensors can perform self-calibration & self-assessments.
- These sensors can notice issues like switch failures, open coils & sensor contamination.
- These sensors optimize manufacturing processes easily that need changes.
- They can store many systems' data.

Disadvantages

The **disadvantages of the smart sensor** include the following.

- Smart sensors' reliability is one of the major drawbacks because if they are stolen or get damaged then they can affect a lot of systems badly.
- It needs both sensors & actuators.
- Sensor calibration has to be managed by an external processor.
- High complexity in wired smart sensors, so the cost is also very high

Applications

The **applications of the smart sensor** include the following.

These sensors play a key role in monitoring different industrial processes like data collecting, measurement taking & transmitting the data to centralized cloud computing platforms wherever data is collected &analyzed for different patterns. So, this collected data can be simply monitored at any time by decision-makers.

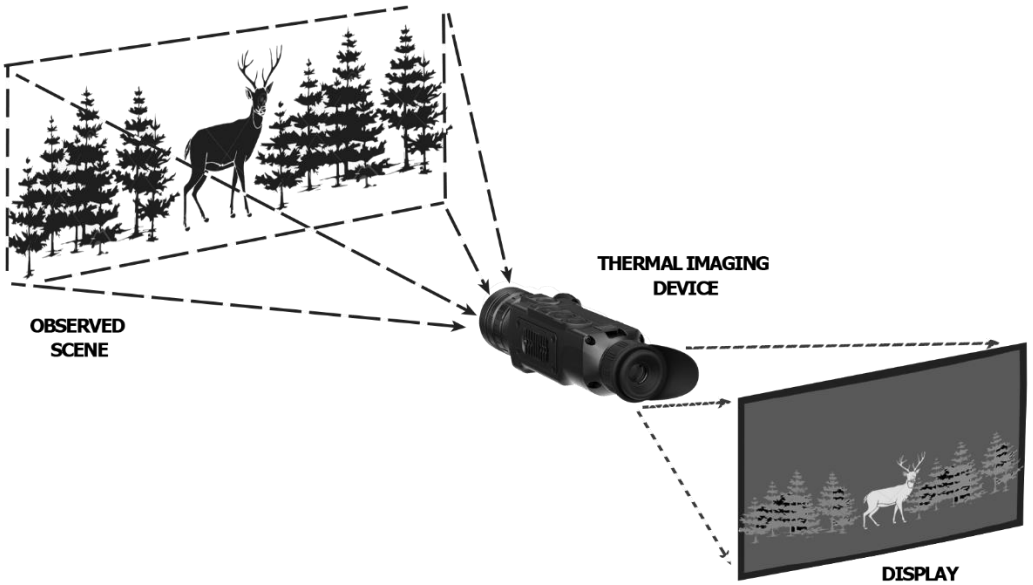
Smart sensors are used mainly for monitoring & control mechanisms in different environments like water level & food monitoring systems, smart grids, traffic monitoring & control, environmental monitoring, conserving energy in artificial

lighting, monitoring of the remote system, and fault diagnostics of equipment, transport & logistics, agriculture, telecommunications, industrial applications, animal tracking, etc.

7.13 Thermal Imagers

In engineering, there are notions of object and background. Objects are ordinary things that have to be detected and examined (humans, vehicles, animals etc.), the background is everything else not covered by the object in the field of view (forest, grass, buildings etc.)

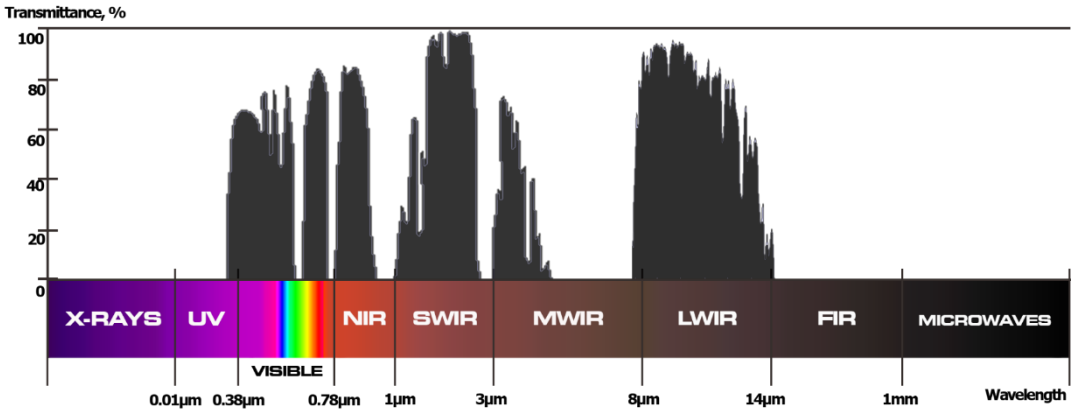
The operation of all thermal imaging systems is based on the perception of the temperature differences between two things i.e. an object against a background and on the conversion of that difference to a visible image. Because all bodies are not heated up equally a picture of IR distribution appears. The higher the difference between an objects IR radiation intensity and the background's IR radiation intensity the more resolvable and with better contrast the thermal image will be. Contemporary thermal imaging devices are capable of detecting temperature differences of 0.015-0.07°C.



Most of the night vision units based on either image intensifier tubes or

CMOS/CCD sensors detect IR radiation in the wavelength range of 0.78-1 µm, which is only a fraction higher than spectral sensitivity of the human eye. Thermal imaging units operate in wavelength range 3-555 µm (MWIR or medium wave infrared) and 8-14 µm (LWIR or long wave infrared). In this wavelength band, ground surface atmospheric layers are transparent for IR radiation and emissivity of observed objects with temperatures -50 - +50°C is the highest.

The thermal imager is an electronic observation device, creating the image of temperature difference in an observed area of space. The fundamental component of every thermal imager is a microbolometer array (thermal sensor) and each picture element of this array (pixel) can measure temperature with high precision.



The advantage of thermal imagers lies in the fact that they do not need any external sources of illumination, they are passive systems which work well in both the daytime and pitch-black nighttime conditions. As mentioned before bad weather conditions such as fog or rain do not create obstacles for thermal imager, these conditions would make ordinary night vision units completely useless.

The operation of all thermal imaging devices can be simply described in the following way:

- The objective lens of the thermal imager shapes a temperature map of anything in the field of view on to the thermal sensor surface (also called temperature difference map)
- The microprocessor and other electronic elements read data from the thermal sensor, process it and create shape in the display, that represents a visual interpretation of the data. This image is then viewed by an observer through an eyepiece or directly on a screen.

Thermal imagers have more in common with digital night vision devices than image intensified night vision devices (commonly referred to as analogue systems) and allow for a greater number of user-defined settings and adjustments.

For instance, brightness and contrast settings, image colour settings, the introduction of auxiliary information in the field of view (current time, battery charge level, icons of active modes etc.), digital zoom, picture-in-picture (displays zoomed image of the observed object or its part in an additional small window) and display OFF functions (used for energy saving and avoiding backlight exposure).

Thermal imaging and digital riflescopes can also have many functions that can aide the shooter such as multiple selectable reticles with various shapes and colours, convenient and fast zeroing functions like “one-shot zeroing” and “Freeze” zeroing, automatic distance-related correction functions, multiple zeroing profiles for different rifles, an indication of side tilt, elevation angle and many more.

In comparison with analogue night vision riflescopes, the reticle in digital and thermal imaging devices is usually “digital”, i.e. the reticle image is overlaid on

the scene image by video processing. With the image of the observed object and reticles being located in the same plane (the display plane) effects such as parallax are eliminated. The reticle is moved electronically which allows for the removal of the mechanical correction elements usually found on analogue riflescopes. Therefore these mechanical correction elements, that require a costly precision manufacturing and assembly process, can be entirely removed from digital and thermal devices.

Thermal imagers can also have built-in video recorders for capturing images and videos of observed objects and many other auxiliary functions, such as wireless data (photo, video) transmission (radio channel, Wi-Fi) to external devices, remote control of the unit (using a mobile device for instance), integration with a laser rangefinder (with data from rangefinder appearing on the screen of the unit) and integration with GPS-sensors (geopositioning) etc.

Chapter 8
Electrical Machines

Construction of DC Motor - Principle of Operation of DC Motor –Torque Equation of Motor - Construction of DC Generator - Principle of Operation of DC Generator – Emf Equation of Generator – Construction of Transformer – Principle of Operation of Transformer

8.1 Introduction

Electrical machines are devices that convert electrical energy into mechanical energy, or vice versa. They are used extensively in a wide range of applications, from small household appliances to large industrial machinery. Electrical machines can be broadly classified into two types: generators and motors.

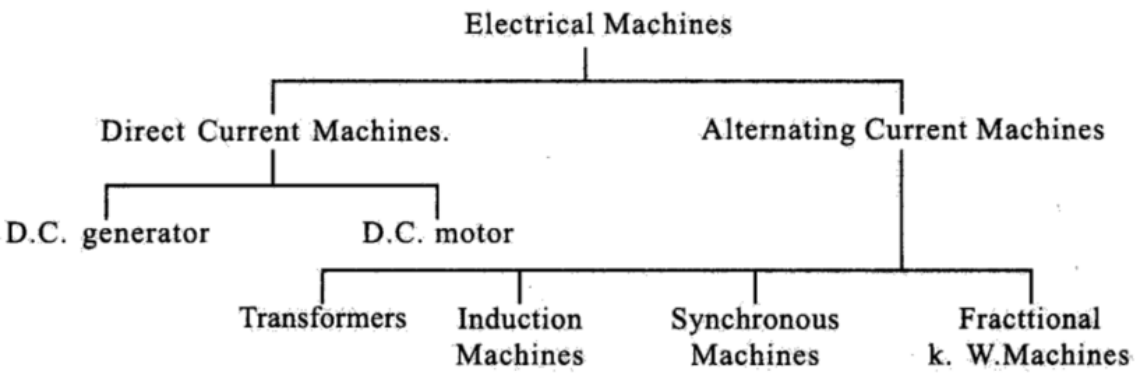
Generators are machines that convert mechanical energy into electrical energy. They work on the principle of electromagnetic induction, whereby a changing magnetic field induces an electric current in a conductor. Generators are used in power plants to generate electricity**.**

Motors, on the other hand, are machines that convert electrical energy into mechanical energy. They work on the principle of electromagnetism, whereby a current-carrying conductor experiences a force in the presence of a magnetic field. Motors are used in a wide range of applications, from powering small household appliances like fans and refrigerators to driving large industrial machinery.

Electrical machines can also be further classified into AC machines and DC machines, depending on the type of current they use. AC machines are those that use alternating current, while DC machines use direct current. AC machines are typically used in high-power applications, while DC machines are commonly used in low-power applications.

Some common types of electrical machines include:

- **Transformers:** devices used to transfer electrical energy between circuits using electromagnetic induction
- **Induction motors:** AC motors that work on the principle of electromagnetic induction
- **Synchronous motors:** AC motors that operate at a fixed speed and are synchronized with the frequency of the AC power source
- **DC motors:** motors that operate using direct current and are commonly used in small appliances and machinery
- **Generators:** machines that convert mechanical energy into electrical energy, commonly used in power plants to generate electricity.



8.2 Construction of DC Motor

A DC motor consists of two main parts: a stator and a rotor. The stator is the stationary part of the motor and contains the field windings, while the rotor is the rotating part and contains the armature windings.

Here is a step-by-step construction process of a simple DC motor:

1. **Frame:** The frame of the motor is usually made of steel or aluminum and provides a rigid support for the other parts of the motor.

2. **Stator:** The stator is made up of a series of electromagnets arranged around the perimeter of the frame. These electromagnets are called field poles, and the number of field poles varies depending on the size of the motor.

3. **Field Windings:** The field windings are copper wires wound around the field poles. When a current flows through these windings, a magnetic field is created, which interacts with the rotor to produce torque.

4. **Rotor:** The rotor is made up of a shaft, a commutator, and armature windings. The armature windings are wound around the rotor and connected to the commutator.

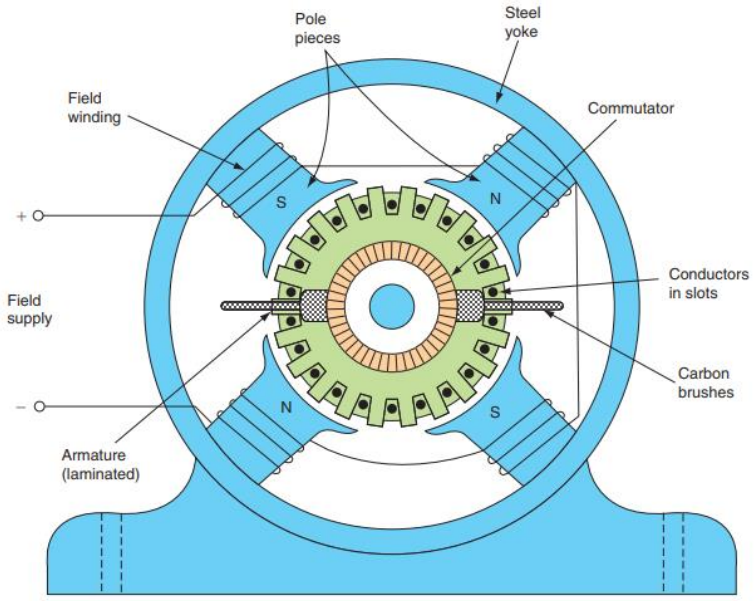
5. **Commutator:** The commutator is a cylindrical device mounted on the rotor shaft that allows the current to flow into and out of the armature windings as the rotor turns. It consists of a series of copper segments insulated from each other.

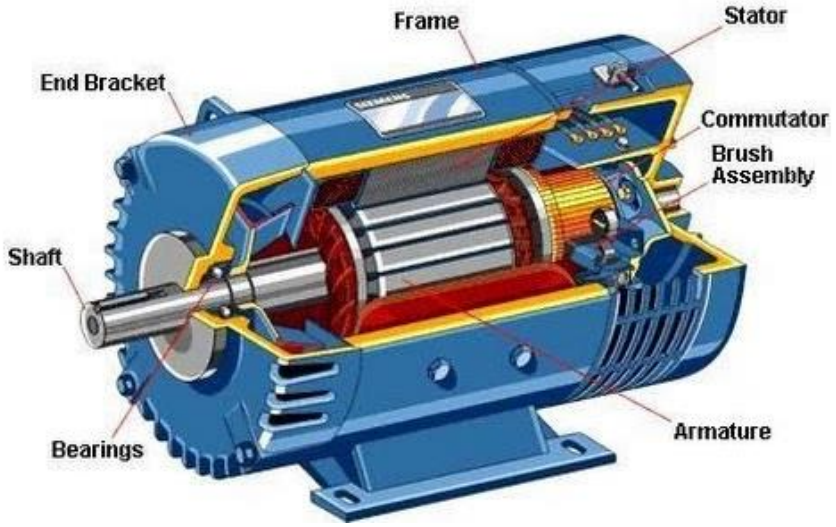
6. **Brushes:** The brushes are made of carbon and are mounted on the frame of the motor. They make contact with the commutator segments and allow the current to flow into and out of the armature windings.

7. **End Caps:** The end caps cover the ends of the motor and protect the internal components from dust and other contaminants.

When a current is applied to the field windings, a magnetic field is created that

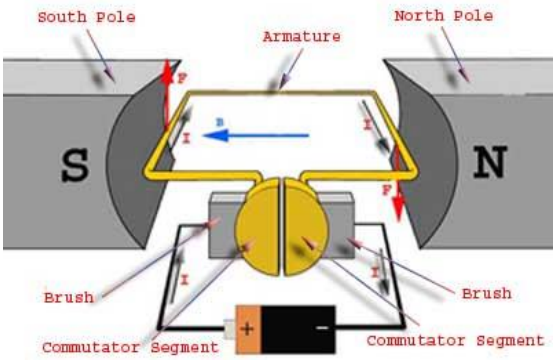
interacts with the magnetic field produced by the armature windings. As the current flows through the armature windings, the rotor turns, producing torque. The commutator ensures that the current flows in the correct direction through the armature windings as the rotor turns, producing a continuous rotation. The brushes maintain contact with the commutator segments, allowing the current to flow into and out of the armature windings.



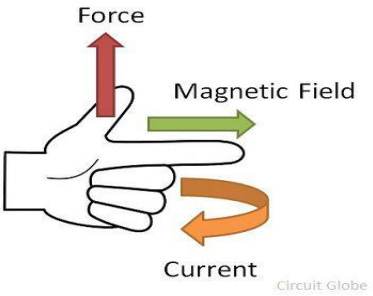


8.3 Principle of Operation of DC Motor

A DC motor in simple words is a device that converts electrical energy (direct current system) into mechanical energy. It works on the principle of Lorentz Law, which states that **"The current carrying conductor placed in a magnetic and electric field experience a force".** And that force is called the Lorentz force. The Fleming left-hand rule gives the direction of the force



- The very basic construction of a DC motor contains a current carrying armature which is connected to the supply end through commutator segments and brushes.
- The armature is placed in between north and south poles of an electromagnet as shown in the diagram above.
- To operate a DC machine as a motor,with the field windings excited and the alternating North and South pole magnetic fields established in the air gap by the stator poles
- A DC current passing via the armature terminals,brushes and commutator causes additional magnetic field to be set up.
- Interaction of this magnetic field with the main magnetic field supplied by the stator poles causes a force to be developed around the conductors.Fleming's left-hand ruleis used to determine the direction of the force acting on the armature conductors of DC motor.



Fleming's left hand rule says that if we extend the index finger, middle finger and thumb of our left-hand perpendicular to each other, in such a way that

- Middle finger is in the direction of current in the conductor, and
- Index finger is along the direction of magnetic field, i.e. north to south pole,
- Thumb indicates the direction of created mechanical force.
- Therefore,force developed in all the conductors is uni-directional.These force acting on the shaft give rise to Torque.
- Due to electromagnetic torque on the armature conductors, the armature starts revolving.
- As the coil rotates, magnetic flux through it changes and an induced emf E is producedas per faraday's law.
- As per Lenz'slaw,this induced emf opposes the applied voltage to the armature.hence, It is called back emf.
- $E_b = P\Phi ZN/60A$

Current flowing in the coil is given by

$$I = \frac{V - Eb}{R}$$

8.4 Torque Equation of Motor

When a DC machine is loaded either as a motor or as a generator, the rotor conductors carry current. These conductors lie in the magnetic field of the air gap.Thus, each conductor experiences a force. The conductors lie near the surface of the rotor at a common radius from its centre. Hence, a torque is

produced around the circumference of the rotor, and the rotor starts rotating.

When the machine operates as a generator at a constant speed, this torque is equal and opposite to that provided by the prime mover.When the machine is operating as a motor, the torque is transferred to the shaft of the rotor and drives the mechanical load. The expression is the same for the generator and motor.

When the current-carrying current is placed in the magnetic field, a force is exerted or it which exerts turning moment or torque F x r. This torque is produced due to the electromagnetic effect, hence is called **Electromagnetic torque.**

The torque which is produced in the armature is not fully used at the shaft for doing the useful work. Some part of it gets lost due to mechanical losses. The torque which is used for doing useful work in known as the **shaft torque**.

Since,

$$V = E_b + I_a R_a \quad \ldots\ldots(1)$$

Multiplying the equation (1) by I_a we get

$$VI_a = E_b I_a + I_a^2 R_a \quad \ldots\ldots(2)$$

Where,

VI_a is the electrical power input to the armature.

$I^2_a R_a$ is the copper loss in the armature.

We know that,

Total electrical power supplied to the armature = Mechanical power developed by the armature + losses due to armature resistance

Now, the mechanical power developed by the armature is Pm,

$$P_m = F_b I_a \ldots\ldots(3)$$

Also, the mechanical power that rotates the armature can be given regarding

torque T and speed n.

$$P_m = \omega T = 2\pi nT \ \ldots\ldots (4)$$

Where n is in revolution per seconds (rps) and T is in Newton-Meter.

Hence,

$$2\pi nT = E_b I_a \quad \text{or}$$

$$T = \frac{E_b I_a}{2\pi n}$$

But,

$$E_b = \frac{\varphi ZNP}{60\ A}$$

Where N is the speed in revolution per minute (rpm) and

$$n = \frac{N}{60}$$

Where n is the speed in (rps).

Therefore,

$$E_b = \frac{\varphi ZnP}{A}$$

So, the torque equation is given as:

$$T = \frac{\varphi ZP}{2\pi A} . I_a$$

For a particular DC Motor, the number of poles (P) and the number of conductors per parallel path (Z/A) are constant.

$$T = K\varphi I_a$$

Where

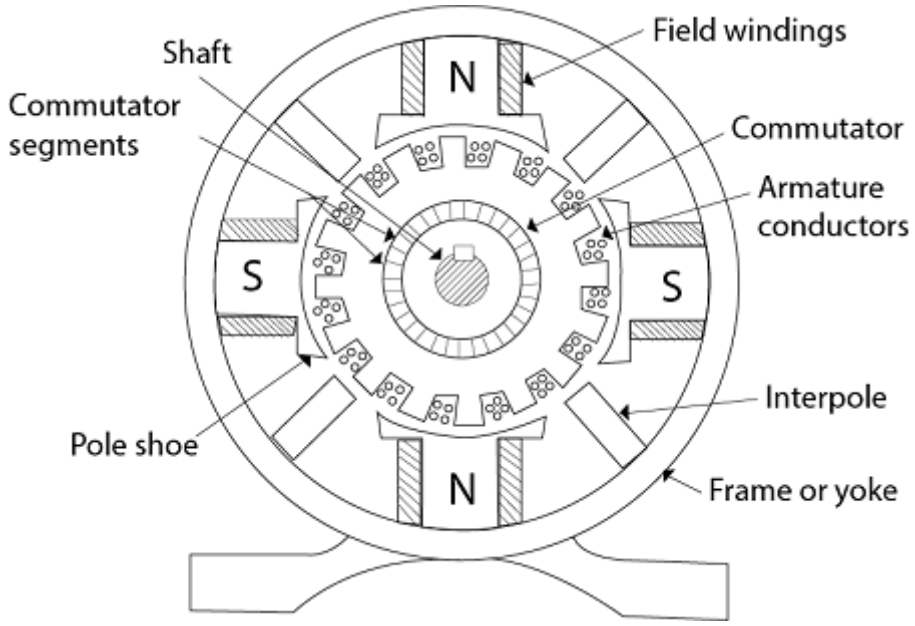
$$K = \frac{ZP}{2\pi A} \quad \text{or}$$

$$T \propto \varphi I_a \ldots \ldots (5)$$

Thus, from the above equation (5) it is clear that the torque produced in the armature is directly proportional to the flux per pole and the armature current. Moreover, the direction of electromagnetic torque developed in the armature depends upon the current in armature conductors. If either of the two is reversed the direction of torque produced is reversed and hence the direction of rotation. But when both are reversed, and direction of torque does not change.

8.5 Construction of DC Generator

A DC generator consists of two main parts: the stator and the rotor.

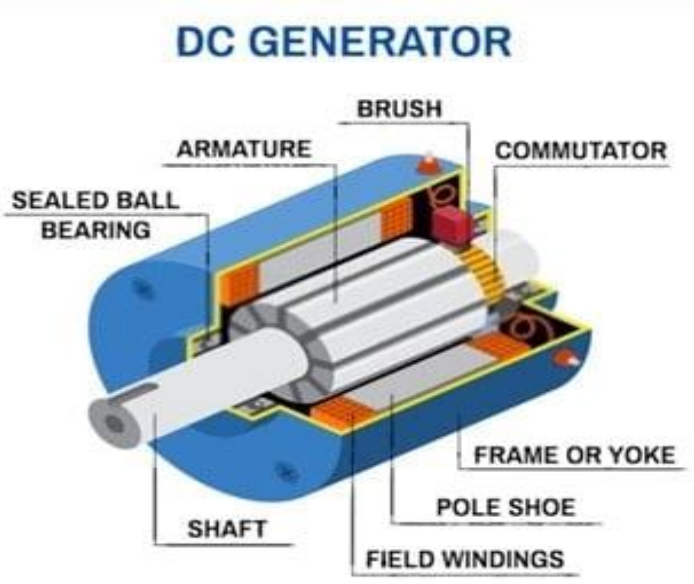


The stator is the stationary part of the generator and consists of a cylindrical frame made of cast iron or steel. The frame is mounted on a base and houses the field poles, which are electromagnets made of laminated steel. The field poles are evenly spaced around the inner circumference of the frame and are connected in series to form a single magnetic circuit.

The rotor is the rotating part of the generator and is mounted on a shaft that is supported by bearings in the end frames of the generator. The rotor consists of a central iron core, which is laminated to reduce eddy currents and hysteresis losses. The iron core is surrounded by the armature winding, which is made of insulated copper wire wound around the core. The armature winding is connected to the commutator, which is a segmented ring made of copper that is mounted on the shaft.

When the rotor is turned, the armature winding passes through the magnetic field produced by the field poles in the stator, inducing an electromotive force (EMF) in the armature winding. The direction of the EMF depends on the direction of the motion of the armature winding relative to the magnetic field, according to Faraday's law of electromagnetic induction.

The commutator and brushes allow the current to be collected from the armature winding and fed into an external circuit. The brushes are made of carbon or graphite and are mounted on stationary holders that press against the commutator segments as the rotor turns. The brushes maintain contact with the commutator segments through a spring mechanism and transfer the current from the armature winding to the external circuit.



Overall, the construction of a DC generator is designed to convert mechanical energy into electrical energy through the use of rotating magnetic fields and induced EMF in the armature winding.

8.6 Principle of Operation of DC Generator

Generators works on the principle of dynamically induced emf.

Energy conversion in dc generator takes place in such a way that whenever a moving coil cuts the magnetic flux, emf (electromotive force) is induced in that coil or conductor according to the faraday law of electromagnetic induction.

Working of DC Generator: DC generator has two types of windings which are termed as Armature winding and Field winding.

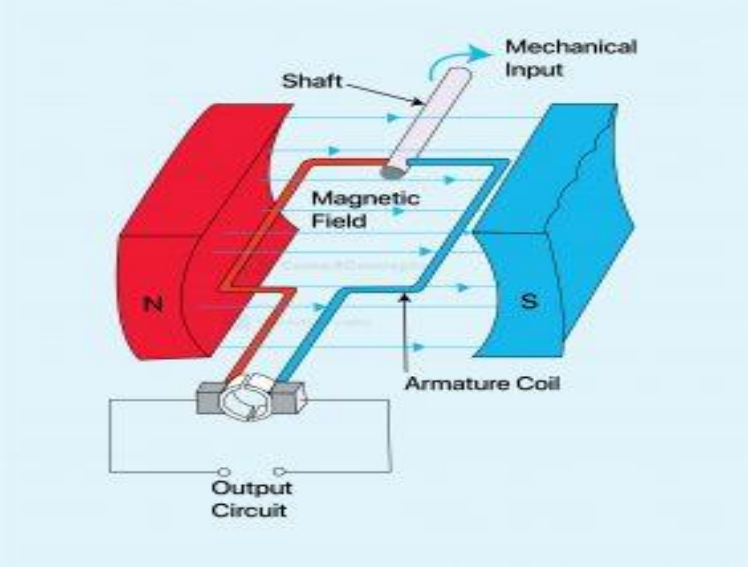
Field Winding: Field winding applies to that winding which produces main magnetic field in a machine. In case of dc generator, field winding is applied on the stator (stationary part) of machine.

Armature Winding: Armature winding applies to that winding where main voltage is induced in the machine. In dc generator, armature windings are placed on the rotor (rotating part).

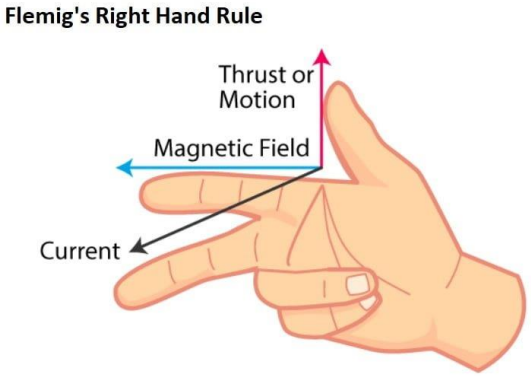
Explanation:

DC voltage is applied to the stator field coils in order to produce constant electromagnetic field (Field winding). Armature windings are applied on the rotor which is installed on the rotating shaft of dc generator. Armature coils of the rotor are made to rotate with the help of mechanical shaft through constant stator magnetic field. Once the armature conductors rotate in a steady magnetic field, an electromagnetically emf is induced within the armature conductors according to the faraday law of electromagnetic induction.

The magnitude of induced emf depends on the number of magnetic lines of force linking with the moving conductor (i.e. rate of change of flux). Emf induced in the coil will cause the current to flow if the circuit is closed. Direction of induced current in dc generator is given by Fleming right hand rule.



Fleming right hand rule: Fleming right hand rule is used to know the direction of induced current in generators. According to this rule, open the right hand in such a way that all the three fingers are perpendicular to each other. After that, align the right hand in such a way that thumb points in the direction of moving coil (force) and let the fore finger move in the direction of magnetic field. Once it's done, middle finger indicates the direction of induced current.



We can say that after every half rotation (when coil is perpendicular to magnetic

field),direction of motion of that particular coil will be reversed. Hence direction of induce current also changes. In simple words, rotating coil (armature) produces alternating current at the output. The below diagram indicates the direction of induced current after every half rotation of coil. Here the question arises: How can we generate dc voltage at the output? In order to have a dc voltage at the output, split rings are used in dc generator. These rings connect between the armature conductors and stationary brushes. As the name of split ring indicates, there is a vertical split between the rings (i.e. one portion of ring doesn't make contact with the other portion of ring since there is a gap between them). Brushes are used for carrying current to the external load circuit. When coil rotates and move from one magnetic field pole to the other (opposite) pole, direction of induce current changes. Similarly, split rings are also rotating change their position at the same time. Because of this, there is a reversal of making contact of split ring with the brush which can automatically change the contact of wire and brush. Actually both rings will make a contact with the other brush after every half cycle which makes the current to flow in only one direction.

In this way, rectification comes into takes place due to split rings. This whole phenomenon is called commutator. Commutator is used for obtaining a rectified waveform and thereby we get unidirectional induce voltage at the output. Moreover, the numbers of commutator segments are same as the number of armature conductors.

Conclusion: An alternating emf is generated across the armature conductors. Commutator converts alternating voltage produced in the armature winding into unidirectional (dc) voltage across the brushes. This simply means that the current through that is also unidirectional. Hence machine works as dc generator.

8.7 Emf Equation of Generator

Let,

- **P** – number of poles of the machine
- **ϕ** – Flux per pole in Weber.
- **Z** – Total number of armature conductors.
- **N** – Speed of armature in revolution per minute (r.p.m).
- **A** – number of parallel paths in the armature winding.

In one revolution of the armature, the flux cut by one conductor is given as:

$$\text{Flux cut by one conductor} = P\varphi \quad \text{wb} \ldots\ldots (1)$$

Time taken to complete one revolution is given as:

$$t = \frac{60}{N} \quad \text{seconds} \ldots\ldots (2)$$

Therefore, the average induced e.m.f in one conductor will be:

$$e = \frac{P\varphi}{t} \ldots\ldots (3)$$

Putting the value of (t) from Equation (2) in the equation (3) we will get

$$e = \frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \quad \text{volts} \ldots\ldots (4)$$

The number of conductors connected in series in each parallel path = Z/A.

Therefore, the average induced e.m.f across each parallel path or the armature terminals is given by the equation shown below:

$$E = \frac{P\varphi N}{60} \times \frac{Z}{A} = \frac{PZ\varphi N}{60\,A} \quad \text{volts} \quad \text{or}$$

$$E = \frac{PZ\varphi n}{A} \ldots\ldots (5)$$

Where n is the speed in revolution per second (r.p.s) and given as:

$$n = \frac{N}{60}$$

For a given machine, the number of poles and the number of conductors per

parallel path (Z/A) are constant. Hence, equation (5) can be written as:

$$E = K\varphi n$$

Where K is a constant and given as:

$$K = \frac{PZ}{A}$$

Therefore, the average induced emf equation can also be written as:

$$E \propto \varphi n \quad \text{or}$$

$$E = K_1 \varphi N$$

Where K_1 is another constant and hence induced emf equation can be written as:

$$E \propto \varphi N \quad \text{or}$$

$$E \propto \varphi \omega$$

Where ω is the angular velocity in radians/second is represented as:

$$\omega = \frac{2\pi N}{60}$$

Thus, it is clear that the induced emf is directly proportional to the speed and flux per pole. The polarity of induced emf depends upon the direction of the magnetic field and the direction of rotation. If either of the two is reversed the polarity changes, but if two are reversed the polarity remains unchanged.

The induced emf is given by the equation shown below:

$$E_g = \frac{PZ\,\varphi\,N}{60\,A} \quad \text{volts}$$

8.8 Transformers

Transformer is a static device which transfers the electrical energy from one circuit to another circuit, without changing its frequency. The voltage can be raised or lowered in a circuit, but with a proportional increase or decrease in the current ratings.

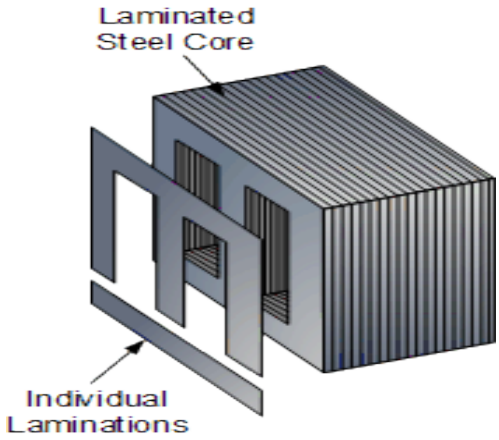
Transformers are used in a variety of applications, including power distribution,

voltage regulation, and impedance matching. They are used to step up the voltage of power generated at power plants for long-distance transmission over power lines, and then step it down to a lower voltage for distribution to homes and businesses. They are also used in electronic devices such as audio amplifiers, to match the output of the amplifier to the input impedance of the speaker. Transformers are available in a range of sizes, from small transformers used in electronic devices to large power transformers used in electrical substations.

8.9 Construction of Transformer

A transformer construction provides a magnetic circuit, known more commonly as the “transformer core”, which is designed to provide a path for the magnetic field to flow around. This magnetic path is necessary for the induction of voltage between the two input and output windings.

However, this type of **transformer construction** where the two windings are wound on separate limbs is not very efficient since the primary and secondary windings are well separated from each other. This results in a low magnetic coupling between the two windings as well as large amounts of magnetic flux leakage from the transformer itself. But as well as this “O” shapes construction, there are different types of “transformer construction” and designs available which are used to overcome these inefficiencies producing a smaller more compact transformer.



The efficiency of a simple transformer construction can be improved by bringing the two windings within close contact with each other thereby improving the magnetic coupling. Increasing and concentrating the magnetic circuit around the coils may improve the magnetic coupling between the two windings, but it also has the effect of increasing the magnetic losses of the transformer core.

As well as providing a low reluctance path for the magnetic field, the core is designed to prevent circulating electric currents within the iron core itself. Circulating currents, called “eddy currents”, cause heating and energy losses within the core decreasing the transformer’s efficiency.

These losses are due mainly to voltages induced in the iron circuit, which is constantly being subjected to the alternating magnetic fields setup by the external sinusoidal supply voltage. One way to reduce these unwanted power losses is to construct the transformer core from thin steel laminations.

In most types of transformer construction, the central iron core is constructed from of a highly permeable material commonly made from thin silicon steel laminations. These thin laminations are assembled together to provide the required magnetic path with the minimum of magnetic losses. The resistivity of the steel sheet itself is high, thus reducing any eddy current loss by making the laminations very thin.

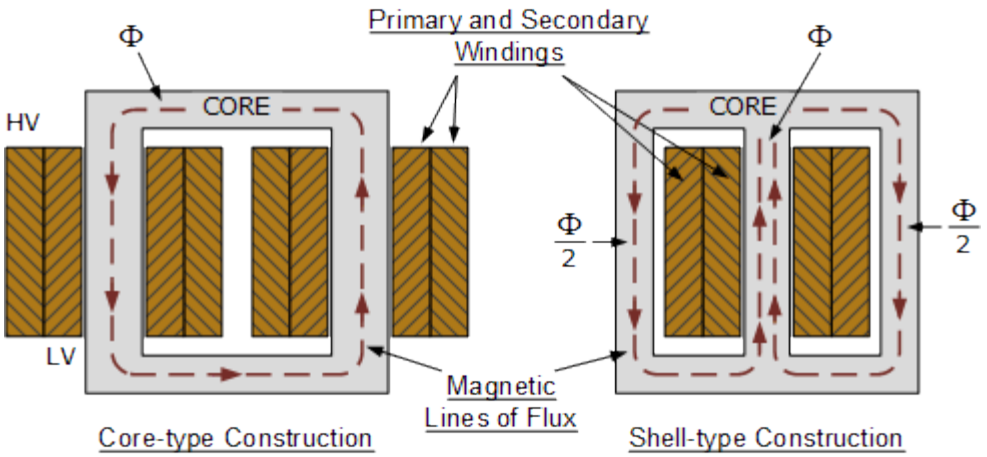
These steel transformer laminations vary in thickness's from between 0.25mm to 0.5mm and as steel is a conductor, the laminations and any fixing studs, rivets or bolts are electrically insulated from each other by a very thin coating of insulating varnish or by the use of an oxide layer on the surface.

Transformer Construction of the Core

Generally, the name associated with the construction of a transformer is dependent upon how the primary and secondary windings are wound around the central laminated steel core. The two most common and basic designs of transformer construction are the **Closed-core Transformer** and the **Shell-core Transformer**.

In the "closed-core" type (core form) transformer, the primary and secondary windings are wound outside and surround the core ring. In the "shell type" (shell form) transformer, the primary and secondary windings pass inside the steel magnetic circuit (core) which forms a shell around the windings as shown below.

Transformer Core Construction



In both types of transformer core design, the magnetic flux linking the primary and secondary windings travels entirely within the core with no loss of magnetic flux through air. In the core type transformer construction, one half of the winding is wrapped around each leg (or limb) of the transformer's magnetic

circuit as shown above.

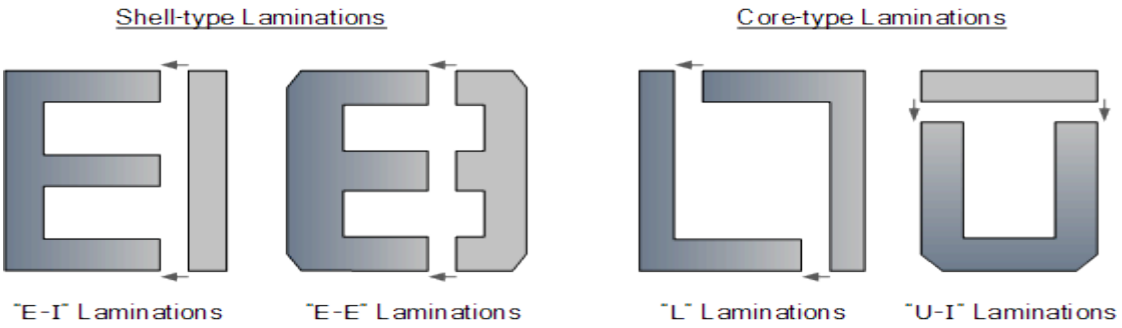
The coils are not arranged with the primary winding on one leg and the secondary on the other but instead half of the primary winding and half of the secondary winding are placed one over the other concentrically on each leg in order to increase magnetic coupling allowing practically all of the magnetic lines of force go through both the primary and secondary windings at the same time. However, with this type of transformer construction, a small percentage of the magnetic lines of force flow outside of the core, and this is called “leakage flux”.

Shell type transformer core’s overcome this leakage flux as both the primary and secondary windings are wound on the same centre leg or limb which has twice the cross-sectional area of the two outer limbs. The advantage here is that the magnetic flux has two closed magnetic paths to flow around external to the coils on both left and right hand sides before returning back to the central coils.
This means that the magnetic flux circulating around the outer limbs of this type of transformer construction is equal to Φ/2. As the magnetic flux has a closed path around the coils, this has the advantage of decreasing core losses and increasing overall efficiency.

Transformer Laminations

But you may be wondering as to how the primary and secondary windings are wound around these laminated iron or steel cores for this types of transformer constructions. The coils are firstly wound on a former which has a cylindrical, rectangular or oval type cross section to suit the construction of the laminated core. In both the shell and core type transformer constructions, in order to mount the coil windings, the individual laminations are stamped or punched out from larger steel sheets and formed into strips of thin steel resembling the letters “E”s, “L”s, “U”s and “I”s as shown below.

Transformer Core Types



These lamination stampings when connected together form the required core shape. For example, two "E" stampings plus two end closing "I" stampings to give an E-I core forming one element of a standard shell-type transformer core. These individual laminations are tightly butted together during it's construction to reduce the reluctance of the air gap at the joints producing a highly saturated magnetic flux density.

Transformer core laminations are usually stacked alternately to each other to produce an overlapping joint with more lamination pairs being added to make up the correct core thickness. This alternate stacking of the laminations also gives the transformer the advantage of reduced flux leakage and iron losses. E-I core laminated transformer construction is mostly used in isolation transformer's, step-up and step-down transformer's as well as the auto transformer.

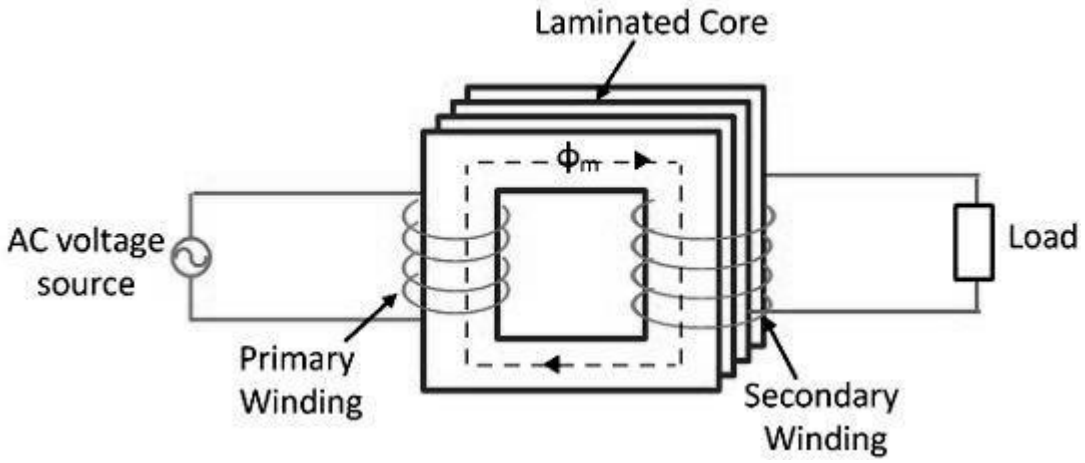
Transformer Winding Arrangements

Transformer windings form another important part of a transformer construction, because they are the main current-carrying conductors wound around the laminated sections of the core. In a single-phase two winding transformer, two windings would be present as shown. The one which is connected to the voltage source and creates the magnetic flux called the primary winding, and the second winding called the secondary in which a voltage is induced as a result of mutual induction.

If the secondary output voltage is less than that of the primary input voltage the transformer is known as a “Step-down Transformer”. If the secondary output voltage is greater than the primary input voltage it is called a “Step-up Transformer”.

8.10 Principle of Operation of Transformer

The working principle of a transformer is based on Faraday's law of electromagnetic induction, which states that a changing magnetic field induces an electromotive force (EMF) in a conductor. In a transformer, two or more coils of wire are wound around a common magnetic core. The coil that is connected to the AC power source is called the primary winding, and the coil that is connected to the load is called the secondary winding.



When an AC voltage is applied to the primary winding, it creates a magnetic field that varies with the frequency of the AC voltage. This magnetic field induces an alternating voltage in the secondary winding, which is proportional to the turns ratio of the primary and secondary windings.

The turns ratio is the ratio of the number of turns in the primary winding to the number of turns in the secondary winding. For example, if a transformer has a turns ratio of 1:10, then the secondary voltage will be one-tenth the value of the

primary voltage. This means that if the primary voltage is 120 volts AC, the secondary voltage will be 12 volts AC.

The magnetic field created by the primary winding induces a voltage in the secondary winding by coupling the magnetic flux through the core. The magnetic flux produced by the primary winding is transferred to the secondary winding, where it induces a voltage. The magnitude of the induced voltage in the secondary winding depends on the number of turns in the secondary winding, the rate of change of the magnetic flux, and the frequency of the AC voltage.

The voltage induced in the secondary winding is in the opposite direction to the voltage induced in the primary winding, due to the polarity of the windings. This means that the voltage across the secondary winding is out of phase with the voltage across the primary winding by 180 degrees. The voltage across the secondary winding is also proportional to the load connected to the secondary winding.

8.11 Emf Equation of Transformer

When a sinusoidal voltage is applied to the primary winding of a transformer, alternating flux ϕ_m sets up in the iron core of the transformer. This sinusoidal flux links with both primary and secondary winding. The function of flux is a sine function.

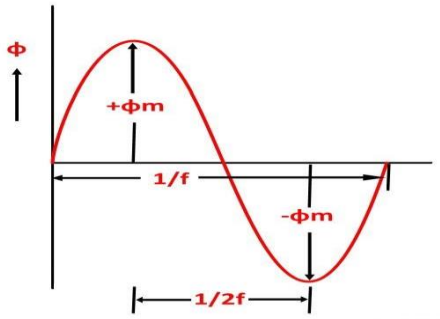
The rate of change of flux with respect to time is derived mathematically.

The derivation of the **EMF Equation** of the transformer is shown below.

Let

- ϕ_m be the maximum value of flux in Weber
- f be the supply frequency in Hz
- N_1 is the number of turns in the primary winding
- N_2 is the number of turns in the secondary winding

Φ is the flux per turn in Weber



As shown in the above figure that the flux changes from + ϕ_m to – ϕ_m in half a cycle of 1/2f seconds.

By Faraday's Law

Let E_1 be the emf induced in the primary winding

$$E_1 = -\frac{d\psi}{dt} \dots\dots\dots (1)$$

Where $\Psi = N_1\phi$

$$\text{Therefore, } E_1 = -N_1 \frac{d\varphi}{dt} \dots\dots\dots (2)$$

Since ϕ is due to AC supply $\phi = \phi_m$ Sinwt

$$E_1 = -N_1 \frac{d}{dt} (\varphi_m \text{ Sinwt})$$

$$E_1 = -N_1 w\varphi_m \text{ Coswt}$$

$$E_1 = N_1 w\varphi_m \text{ Sin}(wt - \pi/2) \dots\dots\dots (3)$$

So the induced emf lags flux by 90 degrees.

Maximum valve of emf

$$E_1 max = N_1 w\varphi_m \dots\dots\dots (4)$$

But w = 2πf

$$E_1 max = 2\pi f N_1 \varphi_m \dots\dots\dots (5)$$

Root mean square RMS value is

$$E_1 = \frac{E_{1max}}{\sqrt{2}} \dots\dots\dots(6)$$

Putting the value of E_1max in equation (6) we get

$$E_1 = \sqrt{2}\pi f N_1 \varphi_m \dots\dots\dots(7)$$

Putting the value of $\pi = 3.14$ in the equation (7) we will get the value of E_1 as

$$E_1 = 4.44 f N_1 \varphi_m \dots\dots\dots(8)$$

Similarly

$$E_2 = \sqrt{2}\pi f N_2 \varphi_m$$

Or

$$E_2 = 4.44 f N_2 \varphi_m \dots\dots\dots(9)$$

Now, equating the equation (8) and (9) we get

$$\frac{E_2}{E_1} = \frac{4.44 f N_2 \varphi_m}{4.44 f N_1 \varphi_m}$$

Or

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

The above equation is called the **turn ratio** where K is known as the transformation ratio.

The equation (8) and (9) can also be written as shown below using the relation ($\phi m = B_m \times A_i$) where A_i is the iron area and B_m is the maximum value of flux density.

$$E_1 = 4.44 N_1 f B_m A_i \text{ Volts} \quad \text{and} \quad E_2 = 4.44 N_2 f B_m A_i \text{ Volts}$$

8.11 Applications of Transformers

Transformers have a wide range of applications in various industries and fields. Some of the common applications of transformers are:

1. **Power distribution:** Transformers are used in power generation stations to step up the voltage of the generated power to reduce transmission losses during long-distance power transmission. They are also used in substations to step down the high voltage power to the lower voltage levels suitable for use in homes, offices, and industries.

2. **Electrical appliances:** Transformers are used in various electrical appliances, such as power adapters, battery chargers, and audio amplifiers, to step down the voltage to a level that is suitable for the appliance.

3. **Lighting:** Transformers are used in lighting systems, such as street lights and fluorescent lamps, to step up the voltage to a level that can ionize the gas inside the lamp and generate light.

4. **Industrial applications:** Transformers are used in various industrial applications, such as welding machines, arc furnaces, and motor controllers, to provide the required voltage and current levels for the equipment.

5. **Electronics:** Transformers are used in electronic circuits, such as power supplies and audio equipment, to provide isolation between the input and output circuits and to step up or step down the voltage as required.

6. **Renewable energy:** Transformers are used in renewable energy systems, such as wind turbines and solar panels, to step up the voltage of the generated power to the required level for feeding into the grid.

7. **Railways:** Transformers are used in railway systems, such as locomotives and train stations, to step up or step down the voltage of the power supply as required by the equipment.

8. **Medicalequipment**: Transformers are used in medical equipment, such as X-ray machines and MRI scanners, to provide the required voltage and current levels for the equipment.

Overall, transformers are essential components in the power and electrical industries, providing efficient and reliable voltage transformation and regulation for a wide range of applications.

Chapter 9
Basics of Power System

Generation of Electric Power – Thermal – Hydro – Wind – Solar – Basic Structure of Power System – Types of Transmission and Distribution Schemes – Representation of Substation

9.1 Introduction

Electric power is the rate at which electrical energy is transferred or converted from one form to another. Electrical energy is the energy carried by an electric current and is the result of the movement of charged particles, such as electrons. Electric power is essential for the operation of modern society and is used in homes, businesses, and industries for lighting, heating, cooling, transportation, and communication.

The unit of measurement for electric power is the watt (W), which is equivalent to one joule per second. Power can be calculated by multiplying the voltage (V) by the current (I), using the formula P = VI. Electrical power is typically generated by converting another form of energy, such as mechanical energy or chemical energy, into electrical energy.

Electric power is transmitted and distributed through an electrical power system, which consists of power generation, transmission, and distribution components. Power generation involves the production of electrical energy from a source, such as a coal-fired power plant, a hydroelectric dam, a wind turbine, or a solar panel. The electrical energy generated is then transmitted over long distances using high-voltage transmission lines to substations, where it is transformed to lower voltages for distribution to end-users. Finally, the electricity is distributed

to homes and businesses through a network of low-voltage distribution lines.

Electric power is a critical component of modern society, and the demand for electricity continues to increase as the population grows and new technologies emerge. The development of new and renewable sources of electricity, such as wind, solar, and geothermal, is important for meeting the increasing demand for electricity while reducing the environmental impact of power generation.

1.2 Generation of Electric Power

Electric power can be generated in various ways depending on the technology used, availability of resources, and cost-effectiveness. The following are some of the most common methods of generating electric power.

1. **Thermal Power Generation:** This method involves burning fossil fuels like coal, natural gas, or oil to heat water into steam, which drives a turbine connected to a generator. This is the most widely used method of electricity generation globally.

2. **Nuclear Power Generation:** Nuclear power plants use nuclear reactions to produce heat that generates steam, which then drives a turbine. This is a reliable and efficient method but has potential safety issues.

3. **Hydroelectric Power Generation:** This method harnesses the kinetic energy of flowing water to turn turbines and generate electricity. Hydroelectric power plants are mostly installed in regions with waterfalls, rapids, or rivers.

4. **Solar Power Generation:** Solar panels convert sunlight into direct current (DC) electricity that is then converted into alternating current (AC) by an inverter. This method is environmentally friendly but requires significant initial investment costs.

5. **Wind Power Generation:** This method uses wind turbines to convert the kinetic energy of the wind into electrical energy. It is a clean and renewable source of energy but depends on the availability and consistency of wind speeds.

6. **Geothermal Power Generation:** This is the process of extracting heat from the Earth's core to produce steam that drives a turbine. It is an environment-friendly method but requires specific geological locations.

7. **Biomass Power Generation:** This method uses organic matter like plant material or animal waste to produce energy through combustion. This is an eco-friendly source of energy but requires a large amount of biomass material.

1.3 Thermal Power Generation

Thermal power generation is the process of generating electricity by converting heat energy into electrical energy. This process involves the use of fossil fuels such as coal, oil or gas to produce the heat required for generating electricity. In simple terms, thermal power generation involves the following basic steps:

1. **Fuel Extraction and Processing:** The first step in thermal power generation is fuel extraction and processing. The fuel, which could be coal, oil or natural gas, is extracted from the earth and processed to make it suitable for use as a source of energy.

2. **Combustion:** Once the fuel has been prepared, it is burned in a combustion chamber to produce heat. The heat generated by burning the fuel is used to generate steam in boilers.

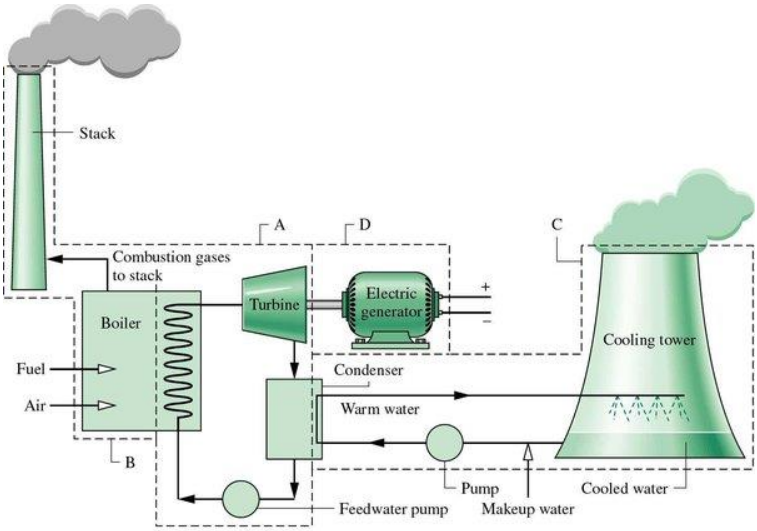
3. **Steam Generation:** The steam generated by the heat produced by

combustion is then used to power turbines. The steam is passed through the blades of the turbine, causing them to rotate at high speed.

4. **Generator:** The rotating turbine drives a generator, which converts the rotational energy into electrical energy. The generator is connected to the electrical grid so that the electricity produced can be distributed to consumers.

5. **Cooling:** Finally, the steam used in the turbine is cooled down and condensed back into water. This water is then reused in the boiler to generate steam again.

Thermal power generation is one of the most widely used methods for generating electricity around the world. While it is an efficient method for producing electrical energy, it does have some serious environmental drawbacks. Burning fossil fuels releases carbon dioxide into the atmosphere, contributing to climate change. Moreover, the extraction and processing of fossil fuels can also have negative environmental impacts. Therefore, there is a growing need to explore alternative sources of energy such as solar, wind and hydroelectric power which are more sustainable and environmentally friendly.



2400 MW PatratuThermalPower Plant in Jharkhand

1.4 Hydro Power Generation

Hydroelectric power generation is the process of generating electrical energy from the energy of falling or flowing water. Hydroelectric power plants convert the kinetic energy of water into electrical energy using a turbine and a generator.

The process of hydroelectric power generation involves the following steps:

1. **Water intake:** The first step in hydroelectric power generation is to capture

the water from a natural source such as a river, lake, or reservoir. The water is channelled through an intake structure and into a pipeline that carries it to the power plant.

2. **Turbine:** The water is then directed towards a turbine, which converts the kinetic energy of the flowing water into mechanical energy. The turbine is typically a large, multi-bladed wheel that rotates when the water hits the blades.

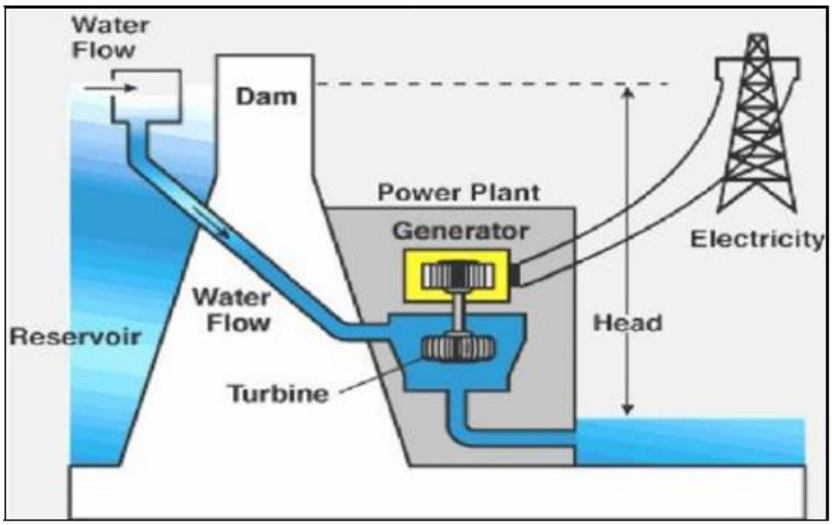
3. **Generator:** The rotating turbine is connected to a generator, which converts the mechanical energy of the turbine into electrical energy. The generator is typically a large electromechanical device that uses the principle of electromagnetic induction to generate electricity.

4. **Transmission:** The electrical energy generated by the generator is transmitted through high-voltage transmission lines to the distribution system, where it is distributed to customers.

There are two main types of hydroelectric power plants: impoundment and run-of-river.

Impoundment plants use a dam to create a reservoir of water that can be used to generate electricity. The water is released from the reservoir and flows through the turbine, generating electricity.

Run-of-river plants do not use a dam and instead rely on the natural flow of the river to generate electricity. The water is channelled through the turbine and then returned to the river.



1530 MW Hydro Power Plant in NathpaJhakri Dam in Himachal Pradesh

Hydroelectric power generation is a clean and renewable source of energy, as it does not produce any greenhouse gas emissions or other pollutants. However, the construction of dams and reservoirs can have environmental impacts, such as the displacement of wildlife and alteration of natural waterways.

1.5 Wind Power Generation

Wind power generation is the process of generating electrical energy from the kinetic energy of the wind. Wind turbines are used to convert the energy of the wind into mechanical energy, which is then converted into electrical energy using a generator.

The process of wind power generation involves the following steps:

1. **Wind turbine:** Wind turbines are large structures that contain blades, a rotor, a nacelle, and a tower. The blades are designed to capture the energy of the wind and rotate the rotor. The rotor is connected to a gearbox, which increases the speed of rotation and transfers the mechanical energy to the generator. The nacelle is the enclosure that houses the gearbox, generator, and other components.

2. **Generator:** The mechanical energy from the gearbox is transferred to the generator, which converts it into electrical energy. The generator is typically a large electromechanical device that uses the principle of electromagnetic induction to generate electricity.

3. **Transmission:** The electrical energy generated by the generator is transmitted through high-voltage transmission lines to the distribution system, where it is distributed to customers.

Wind turbines can be installed onshore or offshore, depending on the location and availability of wind resources. Offshore wind turbines are typically larger and more powerful than onshore turbines, as they are designed to capture the stronger and more consistent winds that are available over water.

Wind power generation is a clean and renewable source of energy, as it does not produce any greenhouse gas emissions or other pollutants. However, wind turbines can have visual and noise impacts on nearby communities, and their installation and operation can have environmental impacts, such as the disturbance of wildlife habitats and the alteration of natural landscapes.

Working principle of Wind Turbine

Wind power generation is the process of harnessing the kinetic energy of wind and converting it into electrical energy using wind turbines. Wind turbines consist of rotor blades, a rotor hub, a gearbox, a generator, and a tower. The working principle of wind power generation can be described in the following steps:

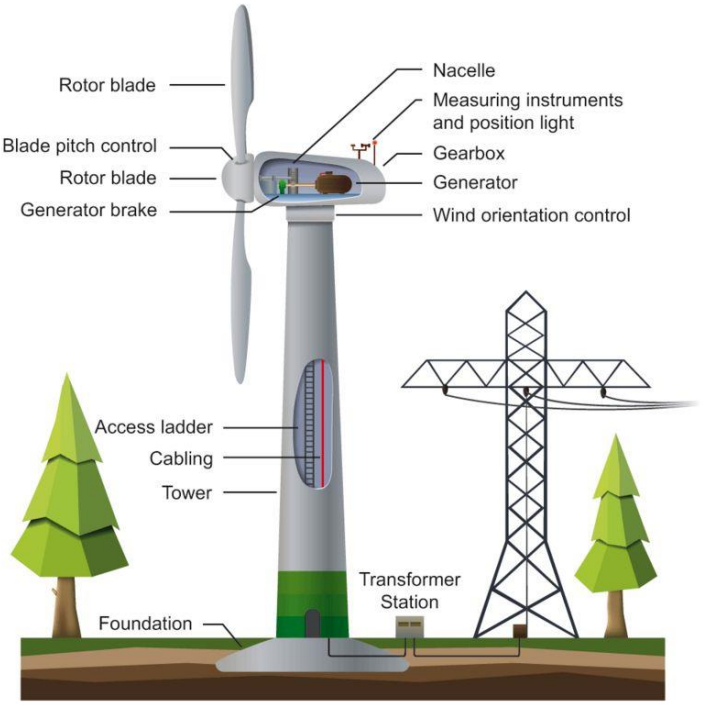
1. **Wind Energy Conversion:** When wind blows across the rotor blades, it causes them to rotate. The rotor hub is connected to the blades and it rotates with them. The rotation of the rotor hub is used to turn a shaft, which is connected to a gearbox.

2. **Gearbox:** The gearbox increases the rotational speed of the rotor hub, which drives a high-speed shaft connected to a generator. The generator converts the kinetic energy of the rotating shaft into electrical energy. The electrical energy generated by the generator is then sent to a transformer, which increases the voltage of the electricity to enable transmission.

3. **Tower:** The wind turbine is mounted on a tall tower to ensure that the rotor blades are exposed to the strongest winds. The tower also provides stability

to the turbine and helps to minimize the impact of vibrations caused by the rotation of the blades.

4. **Transmission:** The electrical energy generated by the wind turbine is sent to a substation using high-voltage transmission lines. At the substation, the electricity is transformed to a higher voltage level for long-distance transmission over the grid. Finally, the electricity is distributed to end-users, such as homes and businesses.



Wind power generation is a clean and renewable source of energy, as it does not produce any emissions or pollutants during operation. However, wind turbines can have environmental impacts, such as noise pollution and potential bird and bat collisions. Wind turbines are typically installed in areas with strong and consistent winds, such as onshore or offshore locations, to maximize their energy output.

1.6 Solar Power Generation

Solar power generation works by capturing the energy from the sun and converting it into electrical energy. This is done through the use of solar panels, which are made up of photovoltaic cells that are designed to capture sunlight and convert it into direct current (DC) electricity.

The photovoltaic cells in the solar panels are made up of a semiconductor material such as silicon, which is able to absorb sunlight and release electrons. When the sunlight hits the cells, it creates an electric field that causes electrons to move around within the cells, generating an electrical current.

The DC electricity generated by the solar panels is then converted into usable AC electricity through the use of an inverter. This AC electricity can be used to power homes, businesses, and other buildings, or it can be fed back into the grid for use by others.

There are two main types of solar power systems: grid-tied and off-grid. Grid-tied systems are connected to the utility grid and allow excess energy to be transferred back into the grid. Off-grid systems, on the other hand, are self-sufficient and can provide power to a home or building even when the grid is down.

One of the biggest advantages of solar power generation is that it is a renewable and sustainable source of energy. The sun is a virtually unlimited source of energy, and solar panels do not produce any emissions or pollutants, making it an environmentally friendly option.

However, one of the downsides of solar power generation is that it can be expensive to install and maintain. Additionally, because solar panels rely on sunlight to produce electricity, they may not be as effective in areas with limited

sunlight or during cloudy weather.

Solar power generation is the process of converting sunlight into electrical energy using photovoltaic (PV) cells. PV cells are made from semiconductor materials, such as silicon, that can absorb photons of light and release electrons, creating an electric current.

The principle operation of solar power generation involves the following steps:

1. **Photovoltaic cells:** The first step in solar power generation is to capture sunlight using photovoltaic cells. The cells are arranged in modules or panels and mounted on a structure that is oriented towards the sun.

2. **Absorption of light:** When sunlight hits the PV cells, it is absorbed by the semiconductor material, causing electrons to be released from their atoms. The released electrons create a flow of electricity.

3. **Direct current (DC) electricity:** The electricity generated by the PV cells is in the form of direct current (DC) electricity. This DC electricity is sent to an inverter, which converts it into alternating current (AC) electricity that can be used to power homes and businesses.

4. **Transmission:** The AC electricity is sent to the distribution system, where it is distributed to customers.

648 MW Solar Power Plant in Kamuthi

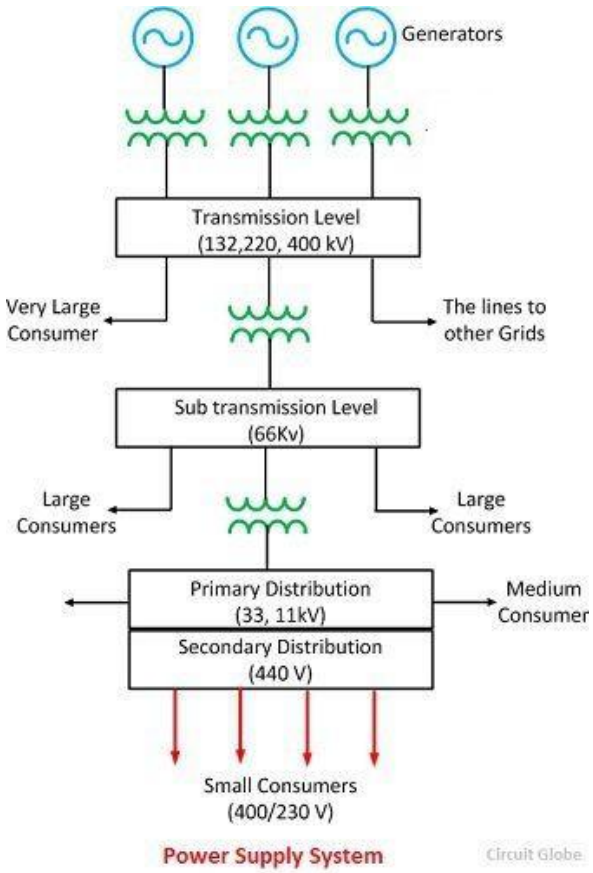
Solar power generation can be installed on rooftops, ground-mounted systems, or integrated into building materials, such as solar shingles or tiles. The amount of electricity generated by a solar power system depends on the amount of sunlight it receives and the efficiency of the PV cells.

Solar power generation is a clean and renewable source of energy, as it does not produce any greenhouse gas emissions or other pollutants. However, the production and disposal of PV cells can have environmental impacts, and the

efficiency of solar power generation is affected by factors such as weather and the angle of the sun.

1.7 Basic Structure of Power System

A power system is an interconnected network of various components, such as generators, transformers, switchgear, and transmission lines, that facilitate the generation, transmission, distribution, and consumption of electric power. The primary function of a power system is to ensure the reliable, safe, and efficient delivery of electricity from power plants to end-users.



The basic components of a power system include:

Generation plants: These are facilities that use various energy sources to

produce electricity.

Transmission lines: These are high-voltage power lines that transport electricity over long distances from generation plants to substations.

Substations: These are facilities where voltage is stepped down from high to low before being distributed to consumers.

Distribution lines: These are low-voltage power lines that deliver electricity from substations to individual customers.

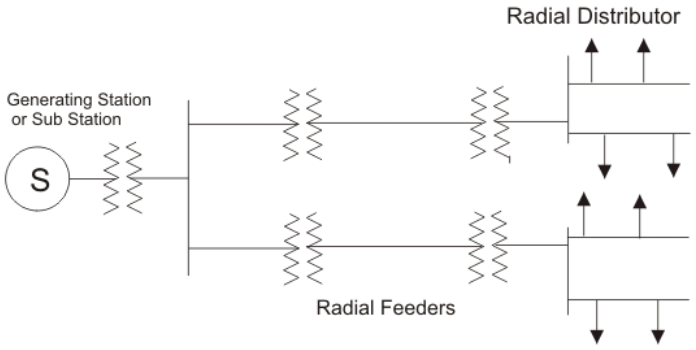
Consumers: These are the end-users who consume electricity for various purposes.

Power systems also require monitoring, control, and protection mechanisms to ensure their operability in various conditions. The power system's stability and reliability are critical for maintaining a steady supply of electricity to meet the growing demands of modern society.

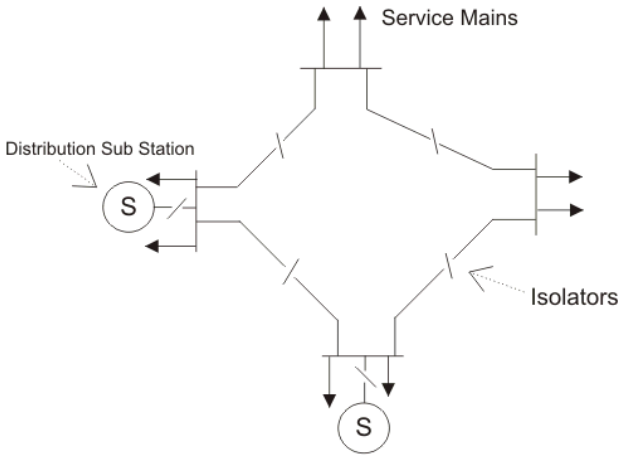
1.8 Types of Transmission and Distribution Schemes

There are different types of transmission and distribution schemes used in electrical power systems to efficiently and reliably transmit and distribute electrical energy from power generation sources to end-users. The main types of transmission and distribution schemes include:

1. **Radial**: The radial scheme is the simplest and most common type of transmission and distribution scheme. It involves a single line that runs from the power source to the end-user, with no loops or alternative paths. This scheme is used for small distribution systems or for isolated loads.



2. **Ring:** The ring scheme involves a closed loop of feeders that are interconnected to form a ring. Electrical power is supplied to the ring at one or more points, and it is distributed to the end-users through multiple paths. This scheme provides redundancy and is used for large distribution systems to ensure reliable power supply.

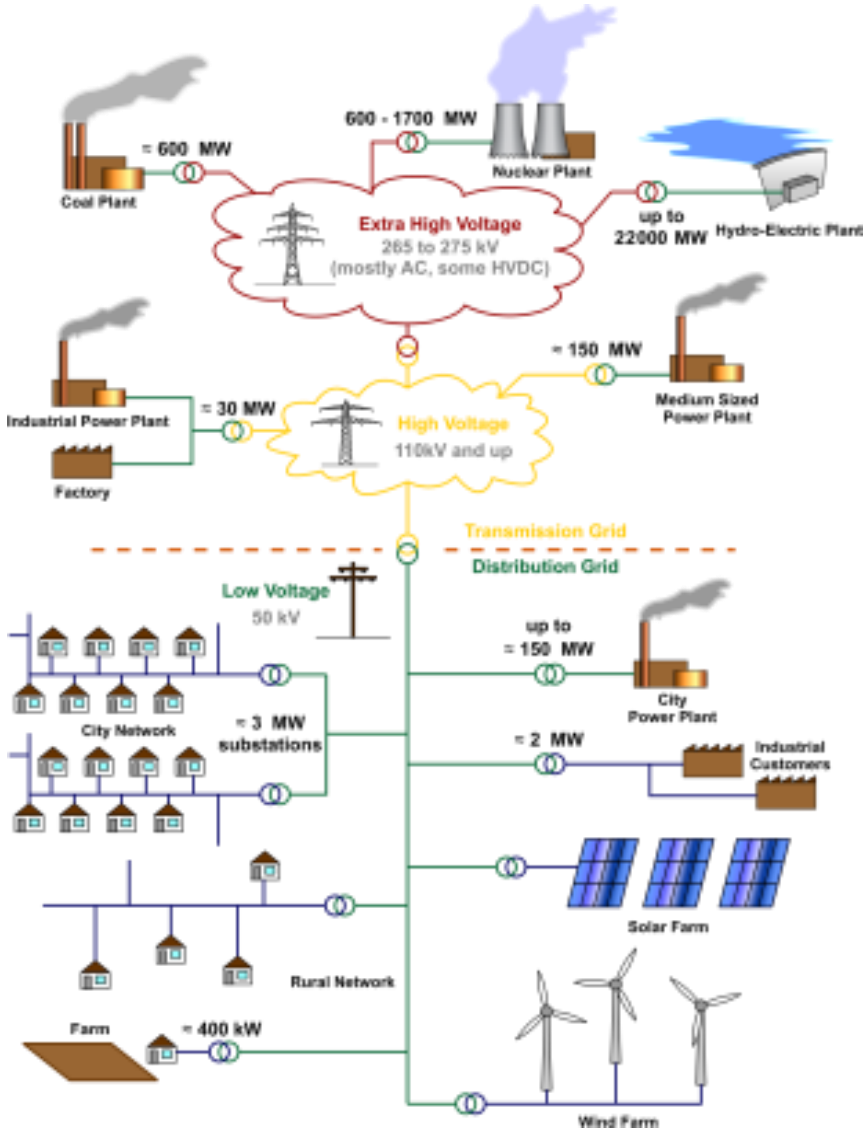


3. **Interconnected:** The interconnected scheme involves multiple power sources that are connected to a large transmission grid. The grid enables power to be transmitted over long distances, and it allows power to be shared between different regions or countries. This scheme provides greater reliability and flexibility in the event of power outages or generation failures.

4. **Mesh:** The mesh scheme involves a network of interconnected transmission lines that provide multiple paths for power to flow. This scheme provides

redundancy and flexibility in the event of line failures or overloads, and it is used for large transmission systems to ensure reliable power supply.

5. **Hybrid:** The hybrid scheme involves a combination of radial, ring, interconnected, and mesh schemes to create a customized transmission and distribution system that meets specific needs. This scheme provides greater flexibility and reliability and is used for complex power systems with diverse sources of power and end-users



.The choice of transmission and distribution scheme depends on thesystem, the type and location of the power sources, and the characteristics of the end-users. The design and operation of transmission and distribution schemes are critical for maintaining the stability and reliability of the power system, and they require advanced planning and coordination to ensure optimal performance.

1.9 Representation of Substation

A substation is a part of an electrical power system that transforms electrical power from high-voltage transmission to lower voltage for distribution to end-users. It is an essential component of the power system, enabling the efficient and reliable transmission and distribution of electricity.

The primary function of a substation is to transform electrical power from high voltage to low voltage and vice versa. This transformation is necessary to minimize power loss during transmission and to ensure that the voltage is appropriate for use by end-users. A substation also includes equipment for protection, monitoring, and control of the power system. The equipment includes transformers, switchgear, circuit breakers, protective relays, voltage regulators, and meters.

Substations can be classified into different types based on their function and location. Some of the common types of substations are:

1. **Transmission Substation:** A transmission substation is located at the end of a high-voltage transmission line and is used to transform the high-voltage power to lower voltage for distribution to the end-users. It is usually located at the outskirts of cities or in remote areas and can be either indoor or outdoor.

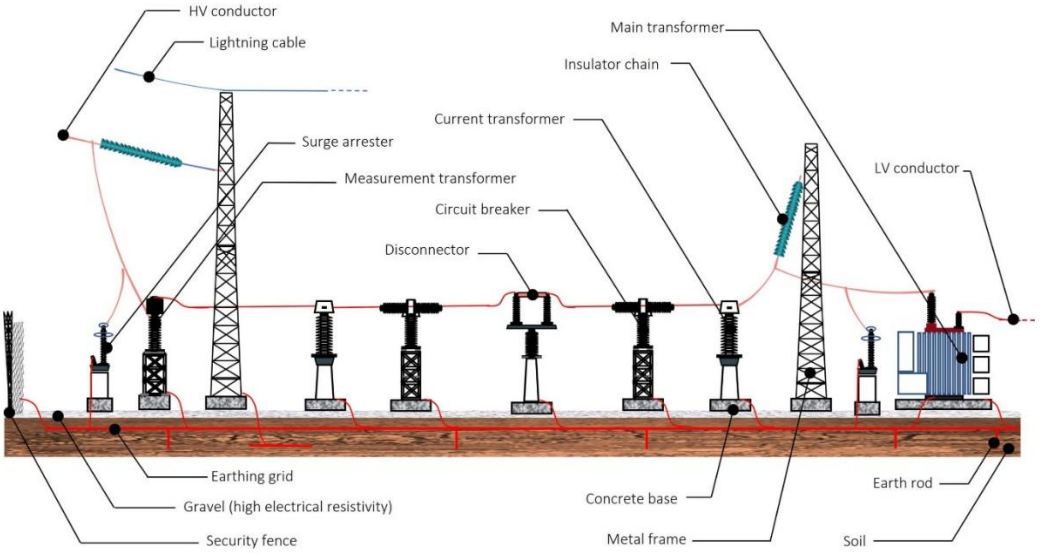
2. **Distribution Substation:** A distribution substation is located near the end-users and is used to transform the power from transmission voltage to lower

voltage for distribution to homes and businesses. It is usually located in urban or suburban areas and can be either indoor or outdoor.

3. **Customer Substation:** A customer substation is located on the premises of an individual customer and is used to transform power from the distribution voltage to a lower voltage appropriate for the customer's use.
4. **Mobile Substation:** A mobile substation is a transportable substation that can be moved to a temporary location in case of emergencies or maintenance.

Substations play a critical role in ensuring the stability and reliability of the power system. They are designed to be safe, efficient, and cost-effective and require regular maintenance and monitoring to ensure optimal performance. The operation and maintenance of substations require specialized skills and expertise and are typically managed by trained professionals.

A substation is represented schematically using a one-line diagram, which is a simplified graphical representation of the electrical components and connections within the substation. The one-line diagram is a standardized graphical representation used by engineers and technicians to design, analyze, and operate the electrical power system.



A single line diagram also called the one-line diagram is a symbolic or graphical representation of a three-phase power system. It has a diagrammatic representation of all the equipment and connections. The electrical elements such as circuit breakers, transformers, bus bars, and conductors, are represented using standardized schematic symbols so that they can be read and understood easily. In a single line diagram, instead of representing each of three phases with separate lines, only a single conductor is represented using a single line. A single line diagram makes it easy to understand an electrical system, particularly in the case of complicated systems in substations. It helps in a detailed study and evaluation of the system and its efficiency.

Advantages of Single Line Diagram:

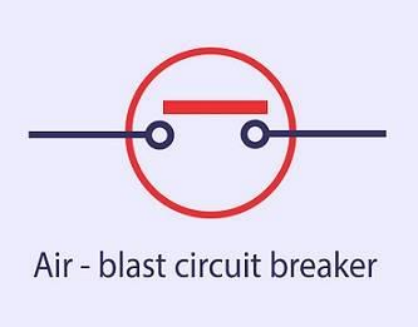
- Gives an overall understanding of the system and eases evaluation.
- It simplifies the troubleshooting process and makes it faster.
- It further ensures the safety of personnel and makes maintenance more convenient.
- It ensures a safer and more reliable operation of the system.

Important symbols for a Single Line Diagram:

Isolating switch: In power substations, it is required to disconnect a part of the

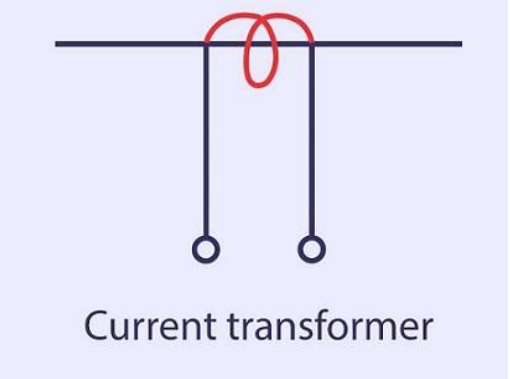
system for general maintenance and repairs. This is accomplished by an isolating switch or an isolator. An isolator is essentially a switch designed to open a circuit under no load. For example, if the entire substation is divided into five sections. Each section can be disconnected with the help of an isolator for maintenance.

Busbar: A busbar is an assembly of bus conductors with associated connection joints and insulating supports. It is a grounded metal enclosure containing factory-mounted, bare or insulated conductors, usually copper or aluminium bars, rods or tubes.

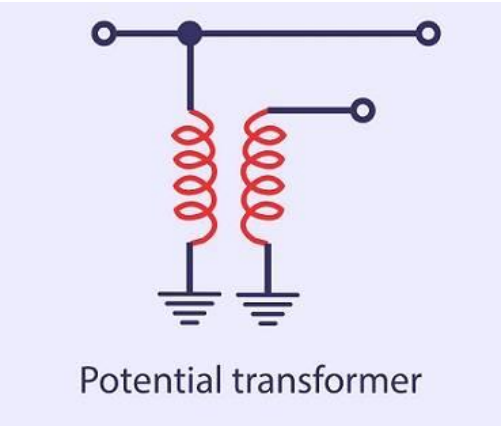


Circuit breaker: A circuit breaker is a circuit component that can open or close a circuit under normal and fault conditions. It is designed such that it can be operated manually under normal conditions and automatically under fault conditions. It is a special type of switching device which can be operated safely under huge current carrying conditions. It is used for timely disconnecting and reconnecting different parts of the power system for protection and control.

Transformers: Transformers are essential components in power transmission and distribution. They are used to step up or step down the voltage. Mostly at a power station, a step-up transformer is used to increase the generated voltage to a higher value. At subsequent substations, a step-down transformer is used to reduce the supply voltage and then finally deliver it at the utilization end.



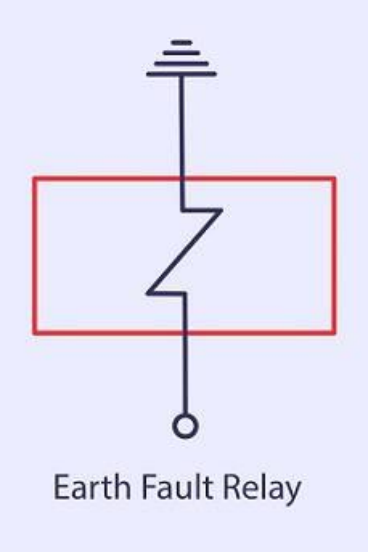
A current transformer is a step-up or step-down transformer that multiplies the current to a known ratio. For example, if a current transformer has a rating of 100/5A, the current on the primary side is 100A and the secondary is 5A. It is a type of instrument transformer. Another type of instrument transformer is the voltage transformer or potential transformer.



A potential transformer is an instrument transformer used for protection and measurement purposes. It measures the high alternating voltage in a power system. It is usually a step-down transformer with a lesser number of windings on the secondary side.

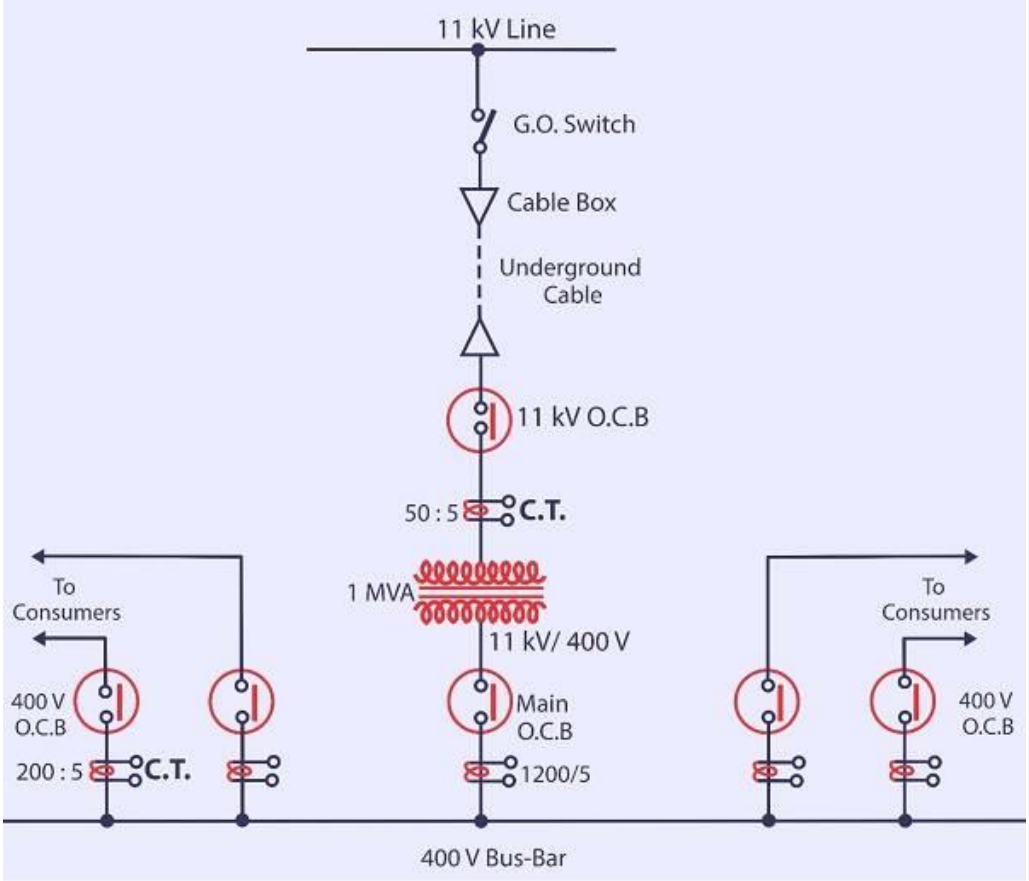
Protective relays: The primary function of protective relays in substations is to cause prompt removal of any element from the service when it suffers a short circuit. Also, it protects when part of a system starts to operate in an abnormal

manner that might cause damage or interfere with the normal operation of the complete system. There are different types of protection relays mainly based on their characteristics, logic, actuating parameters and operation mechanism.



Above, we have discussed some of the important components we see in a single line diagram. There are more components used in an electrical system that have various applications.

Now we shall see an example of a single line diagram of an 11kV/400V indoor substation and its explanation.



The 3-phase, 3-wire 11 kV line is tapped and brought to the gang operating switch installed near the substation. The gang operated switch (G.O. switch) consists of isolators connected to each phase of the 3-phase line. From the G.O. switch, the 11 kV line is brought to the indoor substation as an underground cable. It is then connected to the high voltage or primary side of the transformer (11 kV/400 V) via the 11 kV Oil Circuit Breaker. The transformer steps down the voltage to 400 V, 3-phase, 4-wire.

A single-phase residential load can be connected between any one phase and neutral. A 3-phase, 400 V motor load is to be connected across 3-phase lines directly. Current Transformers are located at suitable places in the substation circuit and supply for the metering and indicating.

The secondary of the main transformer supplies to the busbars through the main circuit breaker. From the busbars 400V, 3-phase, 4 wire supply is given to customers via 400V Circuit breaker. The voltage between any two phases is 400V, and that between one phase and one neutral is 230V.

A Text Book of

Basic Electrical and Electronics Engineering

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